

# Airborne Wind Shear Detection and Warning Systems

## *Second Combined Manufacturers' and Technologists' Conference*

*Compiled by*  
Amos A. Spady, Jr.  
and Roland L. Bowles  
*NASA Langley Research Center*  
*Hampton, Virginia*

Herbert Schlickemaier  
*Federal Aviation Administration*  
*Washington, D.C.*

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## FOREWORD

The Second Combined Manufacturers' and Technologists' Conference was hosted jointly by NASA Langley Research Center (LaRC) and the Federal Aviation Administration (FAA) in Williamsburg, Virginia on October 18-20, 1988. The meeting was co-chaired by Dr. Roland Bowles of LaRC and Herbert Schlickemaier of the FAA. Amos Spady of LaRC and the Science and Technology Corporation coordinated the meeting.

The purpose of the meeting was to transfer significant ongoing results gained during the second year of the NASA/FAA joint Airborne Wind Shear Program to the technical industry and to pose problems of current concern to the combined group. It also provided a forum for manufacturers to review forward-look technology concepts and for technologists to gain an understanding of the problems encountered by the manufacturers during the development of airborne equipment and the FAA certification requirements.

The present document has been compiled to record the essence of the technology updates and discussions which followed each. Updates are represented here through the unedited duplication of the vugraphs, which were generously provided by the respective speakers. When time was available questions were requested in writing. Questions and answers from the floor are included for all sessions. The written questions were presented and answered in the final session and are included in the document. Several of the speakers did not have vugraphs; their talks were transcribed from the recordings of the sessions, edited by the speaker, and are included. Additionally, the opening overview by Mr. David Johnson was transcribed and included to provide the reader with an understanding of the multiple elements included in the Joint Airborne Wind Shear Program.

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**Overview: Second Combined Manufacturers  
and Technologists Conference**

18 October 1988

Dave Johnson, Acting Service Director for the Advanced System Design Service.

Thank you Herb. Good morning and welcome to the Second Combined Manufacturers and Technologists Airborne Wind Shear Review Meeting, here in beautiful Colonial Williamsburg and I hope you are all appreciating this lovely setting, I certainly do. This is going to be an exciting and challenging three days from what Herb tells me according to all of the important work you've been doing and the papers that I've seen so far out in the table, there in the adjoining room, and it's a very ambitious schedule, so I know you want to get on with it and I will be brief. First, I would like to extend my sincere thanks to the NASA team for giving me the opportunity to present the welcoming remarks here this morning and to open the conference. The NASA team, with the FAA, industry and academia participating in this Wind Shear Program make a really formidable team to take on and try to solve this vital, very serious wind shear threat to aviation safety and I think it's really brought home with some of the recent events that we all know about, particularly referencing the United experience in Denver, which you will hear more about this afternoon from Mr. Ireland. The work that NASA and the FAA and various contractor members are performing can only have a major effect in solving the wind shear problem if all members of the team share the information, results and the plans, and that's what this conference is all about and I understand it's an extension from last year's. This very unique relationship allows all of us to go farther than we could individually and produce a lot more results. This information exchange, has a lot of the FAA and the NASA Airborne Wind Shear team to focus on the common

problems and technology, while industry has focused on the means to develop, manufacture and obtain the certification for Airborne Wind Shear assistance. This conference is very timely, considering the recent announcement by Secretary Bernly, concerning the new rule and I quote, "requiring jet airliners to carry equipment that will warn pilots when they encounter unexpected low altitude wind shear." You will hear more about this rule from Steve Morrison this morning. But this is only the beginning, because we need further research to provide predictive wind shear alert technology, not just tell the pilot when he's already experiencing it, and I'm sure you all know that better than I, since I'm relatively new in this game and I'm counting on Herb to bring me up to speed and learn a little bit more about wind shear. Also, when we speak of technology, let's not forget the impact on the pilot. The pilot's vital in the system as we all know. And how the technology is provided to the flight crew to sensible application of flight management and control concepts is essential to successful implementation of the airborne wind shear alerts. Complimentary to the Airborne Wind Shear technology are the advances made with ground based wind shear systems. I noted the agenda items on Thursday for this important segment of wind shear alert systems, and let us all keep the pilots and the controller, and the ground and air based systems in perspective. I think that's really important. It's a system problem and I think it's important that everyone focus on that, keep their perspective and consider the interface and develop the technology such that it does work with the complimentary systems. So to get on with the task before us, I think you need to remember last year's successful conference, Herb tells me that you covered quite a bit of information and was documented in the January 1988 report where you all identified the hazard in aircraft terms, the early results from the sensors technology assessment were presented, the plans for managing and displaying airborne wind shear information were announced. A discussion was held concerning the draft advisory circular the FAA was working on and you were provided with plans and a discussion on the TDWR operational demonstration. This year, building on what you all did last

year, you'll be relating the hazard and how it relates to the system design concept. You'll be looking at the results of the radar lidar and infrared technology assessment and you'll be looking at the results of the FAA/NASA Flight Management Systems efforts and now that the advisory circular is out, there will be further discussion on that, and the clock is starting and how it is apt to be implemented and from Herb tells me, there's going to be a review of the Denver operational TDWR system and I think that will be very exciting for a lot of folks in this field, and probably what Mr. Ireland's going to talk about. So, without going on too much further, I want to, in conclusion say, that I would like to thank you all for your time and effort and for the commitment to this very pressing safety issue. To our partners at NASA, thank you for the close cooperation and the technical expertise that's been provided which has produced all of the results so far and the agenda is full and I won't delay with the points so let's get on with it.

# **TECHNICAL PRESENTATIONS**

**Tuesday, 18 October 1988**

## **Session I. Airborne—Terms of Reference**

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Tools for the Trade  
Wallace M. Gillman, American Airlines

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INDUSTRY TERMS OF REFERENCE

Wallace M. Gillman  
American Airlines  
DFW International Airport, Texas, 75261-9617

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ABSTRACT

An alternate title for this presentation is Tools for the Trade. A brief review of daily operations in the Airline business will be made with emphasis on the decisions made by pilots and the information used to make these decisions. Various wind shears will be discussed as they affect these daily operations. The discussion of tools will focus on airborne reactive and predictive systems. The escape maneuver used to fly out of a severe windshear will be described from a pilot's point of view.



## Session I. Airborne - Terms of Reference

### Tools of the Trade, Wally Gillman, American Airlines

To all of you here, I would like to say, it's a privilege to be able to talk to you today and also very much a challenge. Listening to the previous speakers, I could agree with several things that they've said, first of all, Dave Johnson talked about this being a system problem. That very much is and that's going to basically be the thrust of my presentation, although I say it in different words. Roland said I would have the opportunity to articulate operational requirements. I don't even know what articulate is, so I'm going to have a difficult time there and Herb talked about this meeting being in three phases, hazard characteristics, sensor development, and ground systems, and since we're starting off at the beginning, I guess I'm part of the hazard characteristics.

Let me talk a little bit about myself because I will be referring to some personal experiences here as I go through. I'm a Captain with American Airlines, been flying for over 21 years with American, and about 30 years all together. Seventeen years of that flying was on the line, where day after day after day we'd go out and fly in various weather conditions. For the last 3 1/2 years, I've been a Manager of Flying Engineering for American, which means that my job is to interface with such people as yourself to try to define what our needs are, to try to help develop some equipment. I do test flights, new equipment and new airplanes and when we have certification requirements, then I represent the FAA in certification flights of equipment on our airplane.

Originally, this presentation was supposed to be called Industry: Terms of Reference. That was a little scary to me, so I asked if we could change that and actually the title

now is "Tools for the Trade." Tools for the Trade, and first of all, before I talk about some of these tools, let me talk a little bit about the trade. This viewfoil represents the magnitude of the daily operations of commercial airplanes in the United States in 1987. 6.5 million commercial airline flights. Almost 18,000 daily flights. A little perhaps, personal note, on Sunday the 16th of October, American Airlines flew 231 million revenue passenger miles. That's an awful lot of operations and an awful lot of people travelling an awful lot of miles. I think the point that I would like to make here is that we do this daily, every day and we do it in rain or shine, wind shear, weather conditions, etc. Now, all of you, in this group, are very familiar with wind shears but we tend to focus on microburst quite a bit, but there are all kinds of wind shears that we encounter every day. Almost every one of these flights encounters some kind of wind shear. And a lot of these types of wind shears have caused accidents. A long time ago, an American Airlines airplane hit the dike at La Guardia, Runway 31. That shear is probably due to physical obstruction. And, years ago, going in the midway airport, we always used to have to be careful of the wind shear because of the hangers and the buildings, so those are physical obstructions. We go places where we have wind shears continuously, like in Amsterdam. These types of things are daily occurrences. They're serious. Some of them can be very serious as Roland pointed out in his slide, and we have to take them seriously. But we deal with these things on a daily basis and we need the tools to deal with these things.

If you'll allow me, I'd like to make a few personal references, to talk a little bit about some daily decisions because I think it's important that you understand how we use these tools in daily operation of 18,000 flights a day. Not long ago, as a matter of fact on the 23rd of September, I flew a flight from Chicago to Dusseldorf, Germany, and that particular day, there was a line of storms. So I got on the telephone and talked to the dispatcher. We agreed on a little different routing, adjusted the fuel, and off I went and didn't have any problems. We went through to Dusseldorf with no

problem. The point is, I used some available tools. We used satellite weather depiction, we used weather reports that we had available. We used some radar returns that we had available and we made some decisions. Now, as a result of that we had a non-occurrence. That doesn't mean to say that that event wasn't out there. I know a lot of people out there are concerned when we talk about forward looking sensors, about the fact that by the time you get there the event might not be there, it might be related to a false alarm or something like that. Well in this case, there was no event that I wasn't concerned about a false alarm, I had a smooth trip. Also, about six weeks ago, I flew with a fellow from NASA Langley here, whose name is Charlie Knox, I'm sure Roland knows Charlie. Charlie's got a project on data link, and so I flew him on a Boeing 767 and we went from Dallas to Dulles and I was demonstrating the data link. Now on this particular trip, we rolled out on course and right in front of us was a thunderstorm which was painted on the weather radar. I said to Charlie, "Well, we're going to have to deviate around this thing, but let's take our time, let's look at what's developing on either side of that storm and beyond that storm so we can make our decision in which way to deviate." So we looked at the scope, evaluated the radar returns, and eventually I deviated left. We ended up deviating for about 250 miles and finally went through the hole and went on to Dulles. Again, a smooth ride, a non-event. But I used the tools that were available to make that decision. About a month ago, I was flying a Boeing 767 at Moses Lake, Washington, on a test flight. Part of that test is to fly autoland approaches. We came into Moses Lake and ahead of us was a 747. Now, a 747 is a huge airplane that creates a lot of vortices, and sure enough as we got down on final approach, we started encountering quite a bit of, what you might term as turbulence. The airplane shaking around. We decided to go around rather than continue that approach because we didn't feel the automatic system would be able to handle the shear turbulence conditions as we were encountering them. So that was a decision based upon actually

encountering something, not having any idea of the magnitude that was at the front of us, but not be willing to continue on into it.

Now, those are very recent things, but let me talk a little bit more about something very pertinent to what we're going to talk about here. About one week after Delta 191 accident in Dallas, I was taxiing out to take off on Runway 17 right at DFW Airport. Everybody was very conscience of wind shear after that accident. I remember there was some storms coming in from the northwest and we were watching it as we were in a line of airplanes waiting to take off. We looked at the wind socks. We were listening to the tower reports from the LLWAS system, the winds at various portions around the airport. I was number 2 for take off and I said to my co-pilot, "I'm not going to go on this runway." But just at that time, the number 1 crew in line, Pan Am, said, "I'm not going to go." Then the whole line said, "We're not going to go" then the tower taxied us all down the runway, took us about 15 minutes, down to the other end. By that time the storm had kind of passed by and we all launched to the north. We were using the tools to make those decisions. The tools that we had available. That's the kind of thing that goes on daily. One other example where I wish I had a tool, this is back in the 70's, I was flying co-pilot to Charleston, West Virginia. Now that airport sits on top of the mountain and it's kind of a short runway. You don't like to land with too much speed because you could run off the far end. On the approach, to the runway, you're coming over a great big valley and on that approach, I noticed that the power was way back at idle, very much reduced from what it normally would be. So we discussed the fact that we must have a tail wind at that point, but the tower was reporting a cross wind at the runway. A cross wind almost at our maximum for the airplane, which was a Boeing 727, so we discussed the fact that we better carry a little extra air speed because we were going to encounter a shear. I sure would like to have had a forward looking device so that we could have told how big that shear was going to be. But we carried 25 knots extra airspeed,

which, when you're looking at a short runway on the top of a mountain, is an awful lot of airspeed to carry. Well we got there, and I would say, it felt like two seconds we lost 25 knots. Just like that. I dropped the wing down and just barely saved the landing. We had a reasonable landing, rolled out, and went to the terminal. Nobody knew anything about it, except the guys in the cockpit. I could have used a forward looking sensor for that particular situation.

I've taken quite a bit of time to talk about myself, let's talk about these tools for the trade. I would like to make a little quote from Aeroline, which is a newsletter that's published by ARINC Radio for the AEEC. This is in from the chairman's corner. It says, "We engineers are notorious for becoming entranced with technology for what it can do rather than for what we need it to do. And why? Our industry cannot afford and will not tolerate such a attitude." I'm glad an engineer said that rather than me, you know.

We have some valuable tools coming along. The first one is some valuable training tools that have been developed over the last couple of years as a result of the FAA and industry working on understanding wind shear and particularly microburst. Bob Ireland was involved with this group. They came up with a authoritative training aid that we have used to make changes in our training recently. This is very valuable in our ground training. We are much more aware of the conditions that create microburst and the things to look for that we might be able to detect it and avoid it. In our simulator training, we have microburst models and wind shear models and we have our pilots fly through various wind shear scenarios, practicing detection, detecting when the wind shear is occurring, and then practicing an escape maneuver. Now, we talked about having an unstable approach. When you have an unstable approach, it's time to execute an escape maneuver.

Let me tell you folks, this escape maneuver is not a very nice thing. So let me talk a little bit about escape maneuver. It's something that I don't want to be in if I can avoid it. First of all, when you look at the pilot procedures, they seem pretty straight forward. Use maximum power, rotate to 15 degrees at pitch attitude and then control the flight path. That doesn't seem very difficult, but let me tell you, that is an extreme maneuver from the standpoint of pilot technique. You are operating at a region which you normally don't operate in and it's not something that I want to get involved with if I can avoid it. As far as controlling the flight pass, generally we're talking about stopping a sink so we don't lose altitude and eventually, if you trade off enough air speed in order to stop this sink, you're going to be approaching the limits or stick shaker and you have to respect that and not go into the stick shaker. Well, I would like to take a minute to talk about this escape maneuver. I don't know how many pilots we have in the audience but I would like to take it out of the airplane environment and discuss it from a different perspective. First of all, what is wind shear? Wind shear, I have characterized as stepping off a moving sidewalk like at DFW airport. What happens is that the top part of the body continues to go forward at the same speed but all of a sudden the legs are slowed up because they are no longer on the moving sidewalk. So that's basically the same as wind shear. That's something we can understand and the same affect happens to an airplane. Now, we're dealing with something called angle of attack. And I don't want to get into aerodynamics but, I need to show you what angle attack is before I can continue. (Slide of airfoil at high angle of attack) Here we have an airfoil section, a section through a wing, which the airplane is pointed horizontally. But the airplane is actually going down this path here so that the relative wind is up in that direction. So what we have here is the angular difference between the attitude of the airplane and the flight path of the airplane, this is the angle of attack at that airfoil. When this angle attack exceeds a certain amount, you get over the top surface of the wing instead of getting laminar flow. You lose the lift from the top of the wing and then the airplane

is going to come down! Plain and simple. Particularly if you're in the midst of an escape maneuver in which you already have maximum power. The only way to recover is to lower the nose a little bit, reduce the angle of attack, get laminar flow over the wing and try to fly out. All right, that's all I'm going to talk about angle of attack. Now let's go back to my moving sidewalk analogy. We're going to put a guy on a treadmill (Slide of man on treadmill tilted at steep angle with rear (low) end in the water and net accross high end) Normally the guy moves right along, and there are no problems. He's got lot's of treadmill between the bad water down here and this bad condition up here (net) which represents stick shaker conditions and the end of the treadmill where stall would occur and the guy would fall off. So this guy just marches along doing his thing. But now when we get into wind shear and he's doing the escape maneuver, he gets into a very critical situation where he doesn't have very much to play with. (Slide - similar to previous slide except very little distance between the water and the net) He is very close to disaster down near the water and disaster up near the net and the end of the treadmill. Now we're going to turn the lights out so he can't see how close he is to this stick shaker (net) because there's nothing in the cockpit of older airplanes that shows you where stick shaker is. So our guy is going blindly along hoping that he won't get into the net and hoping he is doing enough to keep from falling into the water. Now, no only am I going to turn the lights out but I'm going to simulate up drafts and down drafts by changing the pitch of the treadmill up and down. Now our guy is going around in the dark trying to stay in this little bit of treadmill while it is pitching up and down. That's kind of like an escape maneuver. It's not a maneuver I want to have to accomplish.

Another valuable tool is the airborne reactive wind shear system that has been under development for a number of years. Bob Ireland and I have been working on an S7 committee of SAE, trying to define the operational characteristics of such a system. It's a reactive airborne system like I fly on the Boeing 767 right now. It is a very

useful tool. We are able to reinforce what we are seeing in the cockpit with this detection alerting system. It reinforces the fact that we're in trouble and that it is due to wind shear. You know, a lot of times there can be turbulence and as I said earlier, day after day, after day, after day we operate into weather conditions where we have shears, we have turbulence, we have deterioration of flight path, and we counter those conditions and continue operating. Now all of a sudden, we've got a device to help us recognize when this shear is beyond the normal limits and annunciates "wind shear" and provides us with flight director guidance for the escape. This is kind of like putting a meter in front of the guy on the treadmill so he can march at the right rate, and stay on the treadmill. So far, we've been doing a pretty good job with this new training program that we've got. They do an excellent job of recognizing the different tilts of the treadmill and marching at the right pace even without this flight director guidance.

I think in terms of time, the next systems that are going to be operational use will be ground based systems. In fact, LLWAS is already in operation. We're going to have some discussions about further development of that tool and development of the terminal doppler weather radar later on in this symposium.

These are exciting tools, but what I would like to focus your attention on is this bottom bullet on my viewfoil where I get back to what Dave Johnson said earlier, in that it's a system problem. You've got to present information to the crew in such a manner that they can utilize the information. When we talk about what happened in Denver on July 11, I'd like you to remember this because there was information there that the crews did not receive the information in a manner that they could operate on it. So if you could just keep this in mind during those presentations, I think that's the kind of thing .. kind of message I'd like to get across. The big thing, as far as I'm



concerned is that the devices on the ground, ought to be able to give us enough information and I can avoid ever getting to that escape maneuver.

The next tools down the line are the tools that are going to come out of all the work that's being done here in airborne sensors. Again this is exciting to have the work that's being done here. We see (we being operational guys in the S7 committee) see this falling into two categories. One set of sensors or some early technology might give us early detection and early escape and the earlier you escape the more treadmill you've got to work with, you know, so the less dangerous that escape maneuver is. Again, though, what we really need to aim at is to have enough information that we can avoid the problem. In case I haven't made my point yet, I just have one viewfoil that might emphasize it. (AVOID, AVOID, AVOID IN LARGE LETTERS) That's what I'm aiming at. Now, what are the characteristics of an avoidance tool. Remember, this has got to be a systems development. We've got to work on these tools to present the information so that we can use it. I see them as having some kind of a situational display that is easy to interpret. I don't have to spend a lot of heads down time. I don't have to spend a lot of manipulative time. I don't have to work a lot of dials. It's a minimum workload. I'm already in an environment during take off or during approach where the workload is heavy. I've got to have something that is very useful for me. I've got to have time or distance (you know we're travelling 3 to 4 miles a minute) I've got to have time to come to some decision and try to coordinate that decision with air traffic control and then I've got to have information that allows me to pick an avoidance path to get out of this environment so that I can avoid it all together. So those are the ingredients I think and characteristics of an avoidance tool.

Thank you very much.

TOOLS

FOR THE TRADE

ORIGINAL PAGE IS  
OF POOR QUALITY

APPLY TO ALL  
APPLY TO ALL

# DAILY OPERATIONS 1987

- 6.5 MILLION COMMERCIAL AIRLINE FLIGHTS IN U.S.
- 17,800 DAILY FLIGHTS

# WINDSHEARS

- GROUND/CORIOLIS EFFECT
- PHYSICAL OBSTRUCTIONS
- SEA BREEZE
- TEMPERATURE INVERSIONS
- MOUNTAIN WAVE
- TURBULENCE
- GUST FRONTS
- THUNDERSTORMS
- MICROBURSTS

## DAILY DECISIONS

- FUEL/ROUTE
- WEATHER AVOIDANCE
- VORTICES - G/A
- TAKEOFF DECISION
- LANDING SHEAR

# TOOLS FOR THE TRADE

# TRAINING

- GROUND
  - AWARENESS
- SIMULATOR
  - DETECTION
  - ESCAPE MANEUVER

## PILOT PROCEDURES

- USE MAXIMUM POWER
- ROTATE TO 15° PITCH ATTITUDE
- CONTROL FLIGHT PATH



## AIRBORNE SYSTEM (REACTIVE)

- DETECTION
- ALERTING
- GUIDANCE

## GROUND BASED EQUIPMENT

- LLWAS
- TDWR
- PRESENTATION IN COCKPIT  
- AVOIDANCE

## AIRBORNE SYSTEMS (PREDICTIVE)

- EARLY DETECTION AND EARLY ESCAPE
- AVOIDANCE

**AVOID**

**AVOID**

**AVOID**

# CHARACTERISTICS OF AVOIDANCE TOOLS

- SITUATIONAL DISPLAY
  - EASY INTERPRETATION
  - MINIMUM WORKLOAD
- TIME (DISTANCE)
  - DECISION
  - ATC COORDINATION
- AVOIDANCE PATH

## **Session I. Airborne—Terms of Reference**

Overview of SAE Committee S-7 ARP 4102/11  
"Airborne Wind Shear Systems"  
Robert L. Ireland, United Airlines

OVERVIEW OF  
SAE COMMITTEE S-7 ARP 4102/11  
"AIRBORNE WINDSHEAR SYSTEMS"

Robert L. Ireland  
Chairman, S-7 Windshear Subcommittee  
United Airlines, Inc.  
Denver, Colorado

ABSTRACT

The windshear subcommittee of SAE Committee S-7 (Flight Deck and Handling Qualities Standards for Transport Aircraft) has developed an Aerospace Recommended Practice (ARP 4102/11) entitled "Airborne Windshear Systems". The subject ARP attempts to combine the most current knowledge of both the pilot community as represented by the standing membership of Committee S-7, and the avionics industry, as represented by consultant members from all companies contemplating windshear device development, in a document to be used as a standard for development of windshear avionics. The first issuance of the ARP concentrated on present position (so-called "in situ") devices, with a mild treatment of look-ahead systems. A revision, currently being considered by the voting membership of the Committee revises and clarifies information on "in situ" systems and adds considerable detail to the look ahead sections. It is noted that, while the sections pertaining to "in situ" systems rely heavily upon knowledge gained in the actual development and testing of such systems, the portions addressing look-ahead devices center more on pilot input of desirable characteristics of predictive systems as pre-development input. Voting on the revision is expected to be completed before the next meeting of S-7 in Tokyo, during the week of October 24, 1988.

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## S.A.E. S-7

### "Airborne Windshear Systems"

- ARP: Aerospace Recommended Practice
- ARP 4109
  - Alerting Systems
  - Detection & Avoidance Systems
- ARP 4109 → ARP 4102/11
- ARP 4102/11 Rev. 1 IN WORK
  - Alerting Systems
  - Detection Systems
  - Avoidance Systems



SAE-S7 Wind Shear ARP - Bob Ireland, United Airlines

First of all, I would like to thank Amos, Herb and everyone else who helped put this together today and particularly for including on the agenda this year some of us from the operational side. I think last year we were just the hecklers. Russell, that's a laser detector wind shear. Just thought I'd get that out of the way. Ok. Before I get started I'd like to compliment the FAA and the ATC, yesterday the system of weather detection and helping airplanes void was working very well. Is there anyone here in the audience who connected through Chicago, yesterday, late afternoon. Just a couple of you. Chicago was essentially in what U.S.A. Today this morning called sky locked, because there were some thunderstorms in the area, I guess some tornado alerts or warnings. It's an example of the system working right and working together and I think although it was inconvenient for some of us to get here for this meeting, as a result of it, it's a very positive sign. Wally alluded to the fact that we have created a committee at SAE that speaks towards the needs in the cockpit. That's what I would like to talk about. The committee is called S7 and what the S7 stands for .. I've never been able to find a person who knows. But the committee itself is known as the Handling Qualities and .....I had it right on the tip of my tongue. It's such a mouthful. Anyway, our committee is composed of representatives from many airlines and many manufacturing firms worldwide and our purpose is to write some recommended practices. They are called Aerospace Recommended Practices for the Society of Automotive Engineers, it's called an ARP and it's a tool that manufacturers can use to understand what the pilots want to see in the cockpit. In particular in this case we formed a subcommittee for the purposes of defining what pilots would like to see in the way of wind shear avionics. Being redundant for many of you, I've coopted so many of you in this room to be part of that committee and so it's a little boring for Sam, Wally, Dave and Sperry folks, there's a great number of you that are already on this committee. We've been working together for about three years now and created a first document that was called ARP 4109 in the numerical categorization

of SAE. It contains information on two basic systems. The alerting systems that are the focus of the new rule that just came out, those systems which detect wind shear only upon entering the phenomenon and providing guidance thereafter and also a second group that we lumped together and called it detection and avoidance. These were systems as we saw them that would look ahead, would see the phenomenon and we hope give enough warning to allow pilots to deviate around it. As many of you are aware, I'm sure, there has been some great discussion about whether it's practical to expect any kind of a device to allow an actual diversion around wind shear as opposed to merely beginning a recovery early. We locked in together in that particular document. 4109 is on the street. It was issued approximately 1 year ago, and the forward looking part of it asks for devices that look ahead 5 miles or more and that the display, that it allows the pilots to deviate around. We realize that wasn't necessarily a totally practical approach and I'll get to that in a minute. For those of you who want to track the documents however, and find out where they've ended up, Herb quit it. Within the last couple of years, SAE's been undertaking a rewrite on all of it's S7 documents and renumbering them. Consequently our wind shear ARP is going to become an annex of a greater ARP and it will become known as 4102 Annex 11. And now I get to the current work of our committee. It's 4102, Annex 11, Rev. 1, it's currently in work .. in fact, it is as we are speaking being voted on by the members of SAE S7, we'll know the results of that voting next week when we all gather in Tokyo and hopefully it's been easily approved. So far the voting indicates that it will be. What we've done in revision 1 is two things. We have expanded the alerting systems section. Primarily in recognition in lessons that are being learned in the operations of the system and the design of them as more and more of them become on the market. Secondly, we have taken the detection and avoidance systems and we split them out into two different systems as we saw them. The detection system being an intermediate device, if you will, the ones that are primarily being focused on for development. Those devices that can give you say 30 seconds to a

minute of advanced warning, be they IR based or laser based. These would be devices that would provide alerting but would not necessarily provide any kind of display because in that time frame, it's probably impractical to try to actually deviate around any such phenomenon. We also continue to have our section which some have referred to as pie in the sky and that's what we call avoidance systems. The pilot community wants to see a system that can look ahead, far enough to provide a geographically based display that can allow aircraft to contact ATC, make arrangements to deviate around these hazards. As much as we may say that's impractical today, we're going to keep pointing in this direction because it is our firm belief that the more we say we want it, the sooner it is that you folks are going to develop such a system for us. I'll hesitate from being too terribly specific on what's in this document because as I said, it is being voted on right now. If people want to submit questions on exactly what we're asking for, I prefer they would just ask me privately because I do not want to put it in the public record as that would be usurping the authority of the S7 members before it has become a public document. Any other questions I would be happy to entertain later and that's all I've got. Thanks a lot.

## **Session I. Airborne—Terms of Reference**

Wind Shear Regulatory Activities  
Steve Morrison, FAA

# **Federal Register**

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**Tuesday  
September 27, 1988**

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## **Part III**

### **Department of Transportation**

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**Federal Aviation Administration**

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**14 CFR Parts 121 and 135  
Airborne Low-Altitude Windshear  
Equipment and Training Requirements;  
Final Rule**

## DEPARTMENT OF TRANSPORTATION

## Federal Aviation Administration

## 14 CFR Parts 121 and 135

[Docket No. 19110; Amdt. Nos. 121-199, 135-27]

## Airborne Low-Altitude Windshear Equipment and Training Requirements

AGENCY: Federal Aviation Administration (FAA), DOT.

ACTION: Final rule.

**SUMMARY:** The FAA amends Part 121 to require airborne low-altitude windshear warning and flight guidance equipment in airplanes and Parts 121 and 135 to require windshear training for flight crewmembers. The National Transportation Safety Board investigations show that low-altitude windshear has been a prime cause of air carrier accidents. This rule is expected to reduce windshear related accidents by training pilots in avoidance and escape techniques and by providing a low-altitude windshear warning system with flight guidance equipment in certain airplanes to increase the margin of safety if windshear is inadvertently encountered.

**DATES:** Effective Date: January 2, 1989.

**Compliance Dates:** 1. Training requirements in §§ 121.409, 121.419, 121.424, and 121.427; §§ 135.345 and 135.351, January 2, 1991.

2. Equipment requirements in § 121.358(a): January 2, 1991, unless certificate holder obtains an extension in accordance with § 121.358(b).

**FOR FURTHER INFORMATION CONTACT:** Gary E. Davis, Project Development Branch (AFS-240), Air Transportation Division, Office of Flight Standards, Federal Aviation Administration, 800 Independence Avenue SW., Washington, DC 20591; Telephone (202) 267-8096.

## SUPPLEMENTARY INFORMATION:

## Background

On June 1, 1987 (52 FR 20560), the FAA published Notice of Proposed Rulemaking (NPRM) 79-11A proposing airborne low-altitude windshear equipment and training requirements. The NPRM was preceded by Advance Notice of Proposed Rulemaking (ANPRM) 79-11 (44 FR 25867, May 3, 1979). The ANPRM invited public participation in addressing low-altitude windshear in the following ways: (1) By placing windshear detection equipment on the ground and transmitting information to the pilot; and (2) by installing equipment aboard the aircraft

that would provide the pilot with windshear information in "real time."

The ANPRM and NPRM were actions in the FAA's continuing efforts to combat the windshear problem. A full discussion of studies, Advisory Circulars, accident/incident data, and NTSB recommendations on windshear appeared in the preamble to NPRM 79-11A. The following information briefly summarizes FAA efforts since 1975.

- In 1975, the National Aeronautics and Space Administration (NASA), in cooperation with the FAA, instituted the Aviation Safety Reporting System (ASRS) whereby safety-related incidents involving aircraft operation are submitted voluntarily and treated anonymously to identify safety problems. Windshear is among the problems identified by reports submitted under this system.

- In 1977, the FAA conducted a study of NTSB reports on aircraft accidents and incidents related to low-altitude windshear that had occurred from 1964 through 1975.

- In May 1977, the FAA amended Part 121 of the Federal Aviation Regulations (FAR) to require air carriers to adopt an approved system for obtaining forecasts and reports of adverse weather conditions, including low-altitude windshear, that could affect the safety of flights on the routes to be flown and at airports to be used.

- The FAA issued Advisory Circular (AC) No. 00-50A, Low Level Wind Shear, to provide guidance in recognizing meteorological conditions that produce windshear phenomena and to recommend certain pilot techniques to minimize the effects of windshear when encountered during takeoff or landing.

- The FAA established a research and development program to examine the hazards associated with low-altitude windshear, develop solutions to the windshear problem, and integrate those solutions into the National Airspace System.

- At 90 major airports within the United States, the FAA installed a ground-based Low-Level Windshear Alert System (LLWAS) capable of detecting the presence of hazardous windshear in the vicinity of the airport at the surface. The FAA intends to install an additional 20 LLWAS's at airports across the nation. In addition, the FAA is working on enhancements to the LLWAS and is cooperating with the National Center for Atmospheric Research on an operational evaluation of a Doppler radar windshear forecasting and alerting system.

- Before issuing ANPRM 79-11, the FAA, through a series of simulator

experiments, investigated the effectiveness of airborne low-altitude windshear systems designed to warn pilots of the existence of windshears and to assist them in transiting or avoiding such shears.

- In November 1983, the FAA issued AC No. 120-41, Criteria For Operational Approval of Airborne Windshear Alerting and Flight Guidance Systems, to provide industry with an acceptable means of obtaining operational approval for the use of various airborne windshear systems on air carrier aircraft.

- In 1983, in response to Public Law 97-369, the FAA contracted with the National Academy of Sciences (NAS) to study "the state of knowledge, alternative approaches and the consequences of windshear alert and severe weather conditions relating to takeoff and landing clearances for commercial and general aviation aircraft." The NAS Report, "Low-Altitude Windshear and Its Hazard to Aviation," was published in late 1983.

- In 1986, the FAA contracted with a consortium of aviation specialists from The Boeing Company, United Airlines, McDonnell Douglas, Lockheed-California, Aviation Weather Associates, and Helliwell, Inc., to produce the Windshear Training Aid document and windshear training videos. The Windshear Training Aid, published and distributed to industry by the FAA, provides guidance on developing flight crew windshear training curricula.

In accordance with FAA research findings and the National Transportation Safety Board (NTSB) recommendations that were based on accident investigations, the FAA proposed in NPRM 79-11A windshear training and airborne equipment requirements as part of a "systems concept" to solve the problem of low-altitude windshear. The concept includes an improved low-altitude windshear weather forecasting technique, ground-based windshear detection equipment, airborne windshear warning and flight guidance, and improved flight crew training.

The FAA has decided after thorough consideration of the comments received on the NPRM to proceed with the proposed windshear training and airborne equipment requirements with minor modifications. A detailed discussion of the major issues raised by commenters and the FAA response to the comments follows.

### Discussion of Comments

Twenty-seven comments were received on the Notice of Proposed Rulemaking. The comments were submitted by air carriers, airline and pilot associations, manufacturers, individuals, and the NTSB. Most comments commended the FAA for taking action to reduce the hazards of windshear encounters. However, several commenters opposed certain proposed requirements. Specific issues that were addressed in the comments were those on applicability; airborne warning devices; flight guidance systems; training; the compliance date; and Advisory Circulars. Several comments also addressed the cost/benefit aspects of the proposed rule. A few comments recommended entirely different approaches to the windshear problem than the one the FAA proposed. Several comments were information on airborne low-altitude windshear warning and flight guidance systems. All issues and categories of comments are discussed below.

#### *Applicability: Equipment*

The proposed requirement in § 121.358 for low-altitude windshear equipment applied to any turbine-powered airplane operated under Part 121 except turbopropeller-powered airplanes. The FAA assumes that when commenters referred to "turbine-powered airplanes", they were using the term as it was defined in proposed § 121.358. The FAA did not propose windshear equipment requirements for any airplanes operated under Parts 91, 125, and 135 because accident history does not justify their inclusion.

- The Air Line Pilots Association (ALPA) objected to the exclusion of reciprocating engine powered and turbopropeller engine powered airplanes from equipment requirements in Part 121. It stated that the table provided in the NPRM showed that a sizeable percentage of the windshear accidents involved the types of airplanes that the proposed rule excluded. The comment also stated that the 1987 Annual Report by the Regional Airlines Association estimates that by 1997 61 million passengers will be carried by members of that Association. According to ALPA these airlines "traditionally use reciprocating engine and turbopropeller powered aircraft."

- The National Transportation Safety Board (NTSB) stated that the "exclusion of reciprocating engine and turbopropeller engine airplanes from this (equipment) requirement may be reasonable based upon the different performance characteristics of those

airplanes." However, NTSB did "not concur with the rationale used to exclude turbine-powered airplanes operated under Parts 91, 125, and 135 from this equipment requirement." NTSB stated that it believed that "the absence of accident data to support the need for including these operations may be due to the comparatively smaller population of turbine-powered airplanes used in those operations and, in some cases, an inability to evaluate accident circumstances because of the absence of flight recorder information." The Aerospace Industries Association (AIA) also objected to the exclusion of turbine-powered airplanes operated under Part 135.

*The FAA's Response:* Although the table provided in the NPRM shows a number of windshear accidents involving reciprocating engine powered and turbopropeller engine powered airplanes, the airplane types involved are older airplanes that have been in service for many years and that are rapidly being retired from Part 121 operations. As pointed out in the NTSB comment, reciprocating engine powered airplanes and turbopropeller engine powered airplanes currently in operation have "different performance characteristics." The FAA agrees with the NTSB that the performance characteristics of these airplanes generally make them less vulnerable in the event of inadvertent entrance into windshear conditions.

Turbine-powered airplanes that are operated under Parts 91, 125, and 135 are excluded from the equipment requirements for several reasons. • Presently no accident/incident data exists to support requiring windshear equipment for these operations. The FAA recently issued a regulation (see 53 FR 26134, July 11, 1988) which requires flight and voice recorders in certain aircraft where they are not now required when those aircraft are operated under Parts 91, 121, 125, and 135. After this rule becomes effective, the FAA will be able to gather more complete data and take appropriate action.

At the present time only reciprocating engine powered and turbopropeller engine powered airplanes are being operated in commuter operations (scheduled operations) under Part 135. On-demand operations under Part 135 and operations under Parts 91 and 125 are conducted with turbine-powered airplanes, but there are fewer flights and these operations are unscheduled operations and therefore do not have the same degree of exposure to hazardous windshear conditions as do the operations covered by this final rule.

Therefore, consistent with the NPRM, the final rule excludes reciprocating engine powered and turbopropeller engine powered airplanes in § 121.358 and does not include any airplanes operated under Parts 91, 125, and 135.

In addition, the FAA has determined that a clarification of "turbopropeller-powered airplanes" as used in proposed § 121.358 is needed in the final rule and has accordingly added the words "with variable pitch propellers with constant speed controls." The addition of these words clarifies the essential design characteristic of turbopropeller-powered airplanes which makes them less vulnerable to the hazards of inadvertent entrance into windshear conditions. The FAA considers this addition necessary in the event that airplanes are manufactured in the future which may have some of the characteristics of turbopropeller-powered airplanes but not variable pitch propellers with constant speed controls. Any such future airplanes would not be excluded from the equipment requirements.

#### *Airborne Low-Altitude Windshear Warning Devices*

Sixteen comments specifically mentioned the proposed requirements for airborne warning devices. Ten favored the requirement, three opposed it, and three opposed certain aspects of the requirement. Opposition to the requirement was primarily directed at the need to retrofit existing airplanes. Concerns about the requirement for airborne warning devices were the following:

- One or more of the predictive systems now being developed could be installed on airplanes and validated for far less cost than present warning systems.
- No research has been conducted to show that a warning device system would add a significant margin of safety over training in windshear procedures.
- Airborne warning devices may be counterproductive to training since they may encourage a pilot to pursue a course that by observation alone he would conclude is dangerous.
- Conditions other than windshear may set off the warning, causing a pilot to abort a take-off or landing, thereby creating a potential hazard where none actually exists.
- Requiring installation of warning devices may slow development of predictive systems.
- Only predictive systems can provide a pilot with information early enough to allow escape.

**The FAA's Response:** The FAA does not agree with the overall position of these comments that requiring an airborne warning device is premature; that the FAA should wait until predictive systems are developed and in the meantime rely solely on training in windshear recognition and escape procedures. The FAA estimates that airborne windshear predictive systems will not be available for operational use for at least another ten years. In the meantime training alone is not enough. Windshear accidents have continued to occur even after windshear training has been incorporated into many certificate holders' training programs. Since windshear training alone cannot guarantee that a pilot will recognize, avoid, or escape windshear conditions, the addition of an airborne warning device will provide flightcrews with an increased margin of safety in inadvertent encounters with low-altitude windshear.

Two systems have already received FAA certification as airborne low-altitude windshear warning and flight guidance devices on various airplanes. In addition, several other manufacturers have made formal application for a Supplemental Type Certificate (STC) for other systems. Any of these systems could provide the flightcrew with enough warning and guidance to enhance the probability of successfully accomplishing the windshear escape procedure for the particular system.

One of the low-altitude windshear warning systems that has been certified and is being used has provided operational data. This data indicated that the warning system provides a significant benefit to the flight crew of the aircraft. This data also indicated that nuisance and false alerts were found to occur at an acceptably low rate to maintain flight crew confidence in the system. (For details see paper titled "Flight Experience with Windshear Detection", by Terry Zweifel presented to the SAE Aerospace Control and Guidance Systems Committee, March 9-11, 1988).

Because of the seriousness of the windshear problem, a regulatory proposal to require implementation of an available low-altitude windshear warning system that could alleviate the problem should not be delayed. The public must be given the maximum available protection from the catastrophic accidents which operating experience has demonstrated can occur.

The requirement for airborne low-altitude windshear warning systems does not mean that the FAA will reduce its commitment to other windshear equipment development. As stated in

the NPRM, the FAA will continue to foster research programs to design better flight guidance and control aids which will improve a pilot's ability to avoid an accident in the event of a windshear encounter. Future FAA action will place emphasis on fostering the development of predictive technology for use in systems to detect and avoid inadvertent entrance into windshear. The FAA will continue pursuing a "systems concept" which includes an improved low-altitude windshear weather forecasting technique, ground-based windshear detection equipment, airborne windshear detection equipment, and improved pilot training.

#### *Flight Guidance*

Except for the National Transportation Safety Board and the Air Line Pilots Association, virtually all of the commenters either opposed or expressed some reservations about the proposed requirement that the approved airborne low-altitude windshear warning system be equipped "with flight guidance." The overall thrust of the opposing comments, like the comments opposed to installing warning devices, was that the cost of retrofitting present aircraft with a flight guidance system far outweighed the potential benefits. ATA on behalf of its member airlines asserted that "the resources that would be required to install guidance systems could better be used for avoidance systems when they become available—an eventuality not too far in the future, according to some."

**The FAA's response:** The FAA does not agree that increased safety would be achieved in a more cost effective way by eliminating the flight guidance requirement and waiting for the windshear detection systems presently in development. As previously stated, the FAA does not believe that fully functional, tested, and reliable windshear detection systems are as close at hand as do several commenters. Nor does the FAA believe that a windshear detection system, if developed, would make a windshear flight guidance system unnecessary. While the FAA agrees that windshear avoidance is the most desirable solution to the windshear problem, 100% avoidance may never be achievable so that an effective flight guidance system may still be highly desirable even if a detection system is developed. The cost/benefit aspects of the flight guidance requirement are discussed under the economic evaluation portion of this preamble. Specific comments regarding the flight guidance requirement are discussed below.

- Several commenters stated that the cost to retrofit existing aircraft with flight guidance systems is disproportionate to the safety gain, especially for aircraft that do not now have go-around or takeoff flight guidance functions in their flight director systems. Some of these commenters pointed out that the Windshear Training Aid states that the manual technique (maximum power and establish a 15 degree body angle pitch on the attitude director indicator) comes within 5-10% of the potential performance using flight guidance. One commenter concluded that "the difference between manual (no guidance) recovery and optimal (but not practical) guidance is something at or less than 5%!"

**The FAA's Response:** The cost/benefit aspects of the flight guidance system requirement are discussed fully under the economic evaluation portion of this preamble. As more fully explained there, the FAA believes that flight guidance systems should be required for turbine-powered airplanes operating under Part 121. The remaining life span of many airplanes already operating under Part 121 is sufficiently long to justify the retrofitting expense of providing low-altitude windshear flight guidance in the event of an inadvertent windshear encounter. The Windshear Training Aid (WTA) statement does not refute this conclusion. However, it should be noted that the conclusions drawn in the WTA with respect to comparing the performance efficiency of the manual technique with flight guidance were based on the assumption that, for the manual technique, the transfer of learning effectiveness from the classroom to the airplane is 100 percent. The conclusion was then drawn that, based on the transfer of learning assumption, the manual technique would be effective 90-95 percent of the time for those few windshears encountered. The behavior pattern resulting from windshear training using various media (e.g. classroom instruction, training devices, cockpit procedures trainers, simulators, etc.) may be degraded over time. Thus, in an actual severe low-altitude windshear encounter, an individual pilot's reaction using the manual technique most likely would not approach the 90-95% potential described in the WTA.

- There is no general industry agreement on present flight guidance algorithms (that is, on just what directions the pilot should be given).

**The FAA's Response:** One hundred percent agreement on existing algorithms may not exist; however, software has been developed that is



adequate to obtain FAA approval. With flight guidance provided by this software, a pilot would have a better chance of taking action necessary for the aircraft to survive an inadvertent encounter with low-altitude windshear.

- Adaptation and modification of older electro-mechanical flight director systems may affect the integrity of the existing systems, thereby derogating safety.

**The FAA's Response:** Modification of older flight director systems should not affect the integrity of those systems. The approved airborne low-altitude windshear warning with flight guidance system to be installed must have been certificated in accordance with the appropriate sections of Part 25 of the FAR and must meet the respective airworthiness and operational approval criteria addressed in AC 25-12 and AC 120-41 or their approved equivalent. This approval process would ensure that the integrity of those systems would not be compromised.

- FAA should not require flight guidance systems until it has completed its characterization of the windshear phenomenon which is not scheduled to be completed until 1991.

**The FAA's Response:** Enough has been learned about the windshear hazard to permit the certification of several windshear systems. The past accident scenarios are well understood and there has been an enormous amount of data generated by the Joint Airport Weather Studies (JAWS) program. While the potential hazards will continue to be studied and further defined there is an adequate base of knowledge to design and certificate a flight guidance system.

- "Optimal" flight guidance may not be practical at this time since many of the present systems require nose down control inputs very close to the ground.

**The FAA's Response:** Optimal flight guidance can only be developed when there is complete knowledge of the characteristics of the air mass in front of the aircraft. Optimal flight guidance is a time dependent variable state which must consider a rapidly changing air mass, as well as special situations (i.e., altitude, speed, configuration, etc.). In the certification process the FAA will evaluate all guidance commands, including nose down commands, for appropriateness. If the optimal guidance strategy for a particular windshear situation requires nose down control inputs so close to the ground that it would cause collision with the ground, the guidance strategy would be unacceptable and would not be certificated. It should be noted that "nose down" does not mean below the

horizon. It means to lower the nose from its present angle.

- While the flight guidance function provides a small increase in the magnitude of the windshear in which an aircraft can successfully operate, that increase only occurs at very high windshear values. Therefore, because of the serious turbulence what would be encountered, this small gain could easily be offset by the pilot's inability to closely follow the commands being given.

**The FAA's Response:** The FAA recognizes that in the worst cases of severe windshear escape may not be possible and, depending upon the cause of the windshear phenomena, flight guidance commands may not be readable because of severe turbulence. However, it is possible to have severe windshear without severe turbulence. Furthermore, for those windshears from which escape is possible, flight guidance provides an additional margin of safety. Between the moderate to severe levels of windshear, flight guidance can provide a gain in performance.

#### Training

Virtually all of the comments received favored the proposed training requirements. A number of comments addressed specific training requirements, particularly those requirements concerning simulator flight training. All specific comments are summarized below.

- Flight Safety International stated that helicopter operators should be excluded from the training requirements for recovery and escape procedures because not enough data exists to develop training in such procedures for helicopters.

**The FAA's Response:** The FAA agrees with the commenter. The FAA has decided to exclude helicopters from the escape training requirements because there are insufficient data on helicopter response to windshear encounters. Accordingly §§ 135.293(a)(7)(ii) and 135.345(b)(6)(ii) have been changed to include the words "except that rotorcraft pilots are not required to be trained in escaping from low-altitude windshear."

- Some comments showed confusion about the intended meaning of the proposed training requirements. Continental Express was concerned that the proposed rule excludes turbopropeller-powered airplanes in § 121.358 from low-altitude windshear equipment requirements without excluding them from the simulator windshear training requirements in subsequent sections of the rule. Flight Engineers' International Association

stated that the proposed flight training requirements do not apply to flight engineers and that the FAA probably intended that they should apply to all cockpit crewmembers. Another commenter was concerned that the required windshear training program might have to be a separate and therefore costly training program.

**The FAA's Response:** As proposed, the language of § 121.409(d) requires simulator windshear flight training only if the airplane is required to be equipped with low-altitude windshear equipment under § 121.358. Therefore, flight training would not be required for pilots flying those turbopropeller powered airplanes excluded from the coverage of § 121.358.

In response to the comment from Flight Engineers' International Association, the proposed amendments to Part 121 included requirements for initial, transition, and recurrent ground training in windshear recognition, avoidance, and escape procedures for pilots and flight engineers, but proposed requirements for flight training in windshear procedures and equipment use were intended only for pilots who are at the controls of the airplane. Current § 121.425 which covers flight training for flight engineers is not being amended by this rulemaking. Windshear ground training in § 121.419 is applicable to all flight crewmembers while windshear flight training in simulators applies only to pilots operating airplanes equipped with low-altitude windshear equipment. If a certificate holder wishes to provide flight training in windshear procedures and equipment for flight engineers, it may do so, but the FAA is not requiring such training.

Finally, in response to the comment concerning windshear training as a separate program, as the FAA explained in the preamble of the proposed rule, the phrase "an approved low-altitude windshear flight training program" was used to refer to the proposed upgraded flight training requirements. The phrase was not intended to mean that there should be a separate training program for those who must provide low-altitude windshear flight training. Instead, the intention is that the approved low-altitude windshear flight training be incorporated into the certificate holder's approved training program.

- The Air Transport Association (ATA) would like to see different wording than that proposed in §§ 121.409(d) and 121.424(d) which stated that a pilot must have training and practice in "at least" and "at least all of" the windshear escape maneuvers and procedures in the operator's approved low-altitude windshear flight

training program. ATA commented that if the FAA's intent was to require that every pilot receive training in every exercise a carrier develops, carriers might be discouraged from developing multiple exercises.

**The FAA's Response:** One means of approval of the windshear training portion of a certificate holder's approved training program is the Windshear Training Aid developed by the FAA and the industry team led by Boeing. In July, 1987, this material was widely distributed to all Part 121 operators and to part 135 operators conducting scheduled operations and within the FAA. The FAA intends that the minimum number of windshear escape maneuvers to be performed in an approved airplane simulator for approved windshear flight training would include at least the maneuvers and procedures associated with the four basic exercises set forth in the Windshear Training Aid. These exercises have the pilot encounter a windshear situation—(1) Before achieving rotation speed on takeoff; (2) during a rotation on takeoff; (3) during an initial climb shortly after takeoff; and (4) during a precision approach. Each certificate holder should develop sufficient variation in the exercises to avoid stereotyping in the training.

In §§ 121.409(d) and 121.424(d)(2) the phrase "at least" is retained, while "all of" has been deleted from § 121.424(d)(2). These changes should make the FAA intent clear, namely that each pilot must receive training in the minimum number of windshear escape maneuvers and procedures that constitute the certificate holder's approved low-altitude windshear flight training program. The "required" training would not include all the possible exercises that an operator might develop for its approved low-altitude windshear training program.

• While logically most windshear flight training should be conducted in a simulator, some commenters wanted an "escape option" in the event that simulators were not available for training. They did not think a pilot's training should be delayed if windshear training in a simulator is temporarily not available. If the pilot could substitute such training in an airplane, at least for some of the training requirements, this would be of help.

**The FAA's Response:** The FAA believes that windshear flight training cannot effectively be given in an airplane because the total environment of a windshear cannot be artificially reproduced in an airplane and it would be too dangerous, in addition to being impractical, to search out actual

windshear conditions. It is practice in the use of proper procedures and techniques under the extreme conditions of windshear that must be accomplished. This can be done safely only in a simulator.

To minimize the overall impact of the training requirements on simulator time, planning will be necessary. Part 121 certificate holders should plan for the downtime necessary to modify simulators and the increased training time, and should anticipate usual malfunction and maintenance downtime. With proper planning the training compliance date of two years after the effective date of the rule January 2, 1989 should allow for modification of simulators without delays in complying with current training requirements. Certificate holders should begin their planning as soon as this rule is published. They may have to begin their low-altitude windshear training as early as one year after the effective date so that they will not have to schedule special training for second-in-command pilots whose last previous recurrent training occurred less than a year earlier.

As a practical matter, most certificate holders use simulators now to meet the six-month training and proficiency check requirements for a pilot in command. The additional flight training required in windshear procedures will add approximately 15 minutes of simulator time. Approximately 80 percent of the pilots and copilots who will be subject to the windshear flight training requirements have at some time received some windshear flight training in simulators. Although certificate holders will have to revise their programs to meet the new requirements, for most pilots and co-pilots actual training time will not necessarily be significantly increased. Since current requirements for recurrent training allow for a 30-day grace period (14 CFR 121.401(b)), air carriers will have flexibility in meeting the recurrent windshear training requirements. Therefore, with proper planning, the simulator windshear flight training requirements should not significantly affect simulator use.

• Proposed § 121.409(d) stated that a certificate holder must use "an approved simulator for each airplane type . . ." Two commenters stated that if this means that each simulator must have the same windshear related avionics as the aircraft that operator is using, the requirement is too restrictive. They state there are two related problems. One, since simulator time is often leased, simulators that are now being leased by some operators may not be adapted

with windshear avionics for the type of windshear equipment the operator will have installed. Thus the operator may have difficulty getting simulator time on simulators with the appropriate windshear avionics. Second, Continental Airlines stated that the "escape maneuver should be generic and not dependent on the hardware installed in the aircraft or simulators."

**The FAA's Response:** While the responses of most trained pilots to windshear are very similar, the performance of the aircraft and the technical characteristics of the windshear equipment differ. Therefore, a pilot needs to practice in a simulator equipped with the same windshear equipment which will be installed in airplanes the pilot will fly. This is especially important since pilot responses to windshear must be performed within seconds. Pilot understanding of equipment differences and aircraft performance differences could be critical.

The availability of simulator time on simulators with the appropriate windshear avionics is a factor that a certificate holder will need to consider and plan for before installing windshear equipment. A certificate holder that is leasing simulator time will need to determine in advance if that simulator will be updated for the appropriate windshear avionics equipment. Also a simulator owner who wants to continue leasing will need to plan for certificate holders' new windshear flight training requirements. Current rules for simulator flight training require a certificate holder to use an approved simulator for each airplane type, and most simulators are capable of being adjusted to allow training for different windshear systems. Therefore, the FAA anticipates that with proper planning and coordination the industry will be able to provide training on a simulator for each airplane type with the appropriate windshear avionics by the compliance date.

• ATA's comment maintains that mandatory windshear escape training and current approach-to-stall maneuvers required in Part 121 may be redundant. Both types of maneuvers involve high power, low speed conditions, and once clear of the windshear, the cleanup recovery from the windshear escape maneuver is identical to the approach-to-stall cleanup recovery.

**The FAA's Response:** The FAA does not agree that these are redundant requirements. While some similarity of maneuvers may exist, the situations and objectives are different. Windshear occurs in a highly unstable environment

while stalls can occur at any time. Approach-to-stall maneuvers are a proficiency requirement while windshear escape maneuvers and procedures do not have a proficiency objective or a performance standard. In windshear flight training the objective is to practice windshear escape procedures in a real time dynamic environment, not to train to a proficiency standard.

- One commenter supported a six-month recurrent windshear ground training requirement but recommended only an annual requirement in an airplane simulator. The commenter stated that "recovery/escape from a low level windshear is basically a mechanical maneuver" and that "as long as the pilot remembers and understands the concept of recovery the probability of success is greatly increased." Therefore, the commenter maintained that "twice annually, monthly, or weekly practice of recovery maneuvers will not ensure one hundred percent" successful recovery.

*The FAA's Response:* To clarify, a six-month recurrent simulator windshear flight training requirement would apply only to a pilot in command (§ 121.427(d) and § 121.443(c)(1)(iii) and (d)). A second in command would be required to have annual recurrent training (§ 121.443(c)(1)). Demonstration of proficiency in escaping windshear is not the objective of the windshear flight training requirement. Adding windshear simulator flight training to pilot recurrency requirements will provide the pilot with practice in the correct procedures for an event which from a statistical standpoint will be infrequently encountered, but to which a pilot is potentially exposed at all times. The FAA believes that practice in windshear escape procedures will prepare pilots to respond immediately and appropriately in an inadvertent windshear encounter.

#### *Effective and Compliance Dates*

Several commenters who objected to the flight guidance portion of the windshear equipment requirement stated that the two-year compliance date was unacceptable for the following reasons:

- It would require too much downtime for aircraft within a fleet.
- It would be impossible for manufacturers of windshear equipment to supply the equipment within a two-year period.
- There are not enough trained mechanics and other technicians to accomplish the required work within two years, and it would be impractical to recruit and train persons for such a

peak-load project since they would likely be laid off afterwards.

- To meet the flight training requirements, simulators would have to be updated, software would have to be developed, and simulators would have considerable downtime. Considering how much simulators are used in pilot flight training and recurrent training and testing, the downtime might seriously interfere with pilot training. In addition, at least one commenter questioned whether the FAA or industry would be responsible for development of the windshear software.

- *The FAA's Response:* Because of the immediacy of the windshear problem, the FAA wants to ensure that there is no unnecessary delay in providing the traveling public with the additional margin of safety sought by these new requirements. However the FAA must allow sufficient time for the resolution of any technical problems with equipment, for production of the needed equipment, and installation and inspection on aircraft. Probably the major limiting factor, other than possible technical problems, is the availability of enough trained mechanics. The FAA recognizes that even if it were practical to train more mechanics to meet increased demand, the necessary training time would make a two-year compliance date for all airplanes impractical. Therefore, to allow time to resolve any technical problems with equipment, for equipment manufacture, order placement, delivery and installation of the equipment, the FAA is permitting a phased compliance schedule for retrofit requirements under certain conditions. The final rule (§ 121.358) requires compliance by two years after the effective date for all airborne equipment requirements unless an operator submits and obtains approval for a retrofit schedule that shows a phased compliance over a 4-year period from the effective date. A request for extension of the compliance date must be submitted no later than 18 months after the effective date. The phased retrofit compliance schedule applies only to airplanes whose date of manufacture was before the effective date of the rule. For the purpose of this section "date of manufacture" means the date the inspection acceptance records reflect that the airplane is complete and meets the FAA Approved Type Design Data. At least 50 percent of such airplanes which are listed on the certificate holder's maintenance operations specifications on the date of submission must be retrofitted within 2 years after the effective date, at least 25 percent more of those airplanes within 3 years, and all of the certificate holder's

affected airplanes within 4 years. Any certificate holder that obtains a compliance date extension must comply with the retrofit schedule and submit status reports every six months until completion of the schedule.

The ground and flight training provisions of the final rule will take effect two years after the effective date of the rule. To make sure that all operators are aware of the compliance dates for the training requirements, the final rule includes new § 121.404 and revised § 135.10 that state the exact date for compliance.

For certificate holders to meet the two-year compliance date for all of their pilots, most certificate holders will want to have the new windshear training program approved one year earlier (i.e., not later than one year from the effective date). In this way the certificate holder will be able to give second in command pilots their required windshear training as part of their regularly scheduled annual recurrent training. Otherwise a certificate holder will have to schedule special training for second-in-command pilots whose last previous recurrent training occurred less than a year earlier.

In order for certificate holders to meet this kind of orderly scheduling, it is important that they begin the approval process as soon as possible so that they will not be faced with last minute training and scheduling problems.

While the final rule does not contain a specific compliance date for the necessary conversion of simulators, it can be seen from the above discussion that most simulators will need to be converted within one year after the final rule takes effect.

Although the final rule allows for phased compliance for retrofits, the FAA assumes that planning will begin at the time of publication of the rule.

#### *Advisory Circulars*

- Two commenters suggested that advisory material being developed by the FAA needs to be seen and commented on before the FAA proceeds to final rule. One stated that it was difficult to discuss the proposal without an opportunity to comment in parallel on the AC defining criteria for approving airborne low-altitude windshear equipment. The second comment stated that the AC should be part of the public record and should receive public input.

*The FAA's response:* Before the NPRM was issued the FAA developed and issued AC 00-50A, Low Level Windshear, AC 120-41, Criteria for Operational Approval of Airborne Windshear Alerting and Flight Guidance

Systems, and the Windshear Training Aid previously discussed in this preamble. In November 1987, the FAA issued AC 25-12, Airworthiness Criteria for the Approval of Airborne Windshear Warning Systems in Transport Category Airplanes. Thus, all of the advisory material necessary for manufacturers and certificate holders to comply with the requirements of this final rule has already been published and by the time the rule takes effect will have been available for a sufficient length of time for all interested persons to be familiar with their contents.

#### *Beyond the Scope of NPRM*

Several comments submitted were beyond the scope of this proposed rulemaking. The FAA has considered these comments as informational and is not responding to them. A summary of such comments follows:

- One comment recommended that the proposed rule be withdrawn and "in its place a requirement adopted that all transport aircraft eventually be equipped with an EFIS instrumentation system." "EFIS" stands for Electronic Flight Information System. This is a flight instrumentation system and flight guidance system that simplifies the integration of information a pilot receives from his flight instruments.
- One comment recommended that all Part 121 aircraft should operate at reduced weights by limiting the fuel, number of passengers, and baggage and cargo anytime that thunderstorms are predicted for an arrival or departure area. According to the comment this would provide the Part 121 aircraft with maneuverability closer to that of Lear jets which have had relatively few windshear accidents.
- Three comments were received which the FAA determined were primarily information about predictive or flight guidance systems that are being developed or are currently on the market. One recommended that the final rule include a requirement for a predictive system with a compliance date two years after approval of such a system.
- One commenter recommended that the FAA require a flight procedure method for transiting windshears based primarily on airspeed/groundspeed comparison.
- NTSB commended the FAA and the industry, led by the Boeing Company, for development of the Windshear Training Aid and stated that it hopes the Training Aid will be the foundation for FAA approval of training curricula implemented by air carriers in complying with the rule. It recommends that an additional training requirement

be added on the use of airborne weather radar for thunderstorm and convective windshear avoidance. It considers this valuable equipment for weather detection during arrival and departure of flights.

- One commenter stated that ground training in windshear detection and escape maneuvers for Parts 125 and 135 pilots was not sufficient and that these pilots should also receive simulator training.
- TWA objected to the requirement to have 14 channels of recording capabilities on flight simulators. It stated that the FAA currently requires 8 channels for certification of flight simulators and that no benefit would be derived from having the additional capabilities. The FAA has not addressed this comment since there is nothing in this rulemaking that states the number of channels required in simulators.

#### **Economic Summary**

The following is a summary of the final cost impact and benefit assessment of a regulation to amend Part 121 of the Federal Aviation Regulations (FAR) to require that certain turbine-powered airplanes be equipped with an approved airborne system that warns a pilot of the presence of hazardous low-altitude windshear conditions and if such windshear conditions are inadvertently encountered, provides flight guidance for a missed approach procedure or an escape maneuver. In addition, the rule requires that all Part 121 operators conduct approved low-altitude windshear flight training in a simulator which has installed in it windshear equipment needed to conform to the airplane type being simulated. The rule further requires that Part 121 and 135 certificate holders' training programs be required to include training concerning flight crewmember recognition of, and escape from, inadvertently encountered hazardous low-altitude windshear conditions as part of their normal ground training.

The NTSB has determined that low-altitude windshear has been the prime cause or a contributing factor in numerous air carrier accidents in the last 20 years. The objective of these rules, therefore, is to prevent or reduce accidents attributed to inadvertent encounters with low-altitude windshear.

The methods and assumptions used to prepare the economic impact estimates for the various changes to Part 121 have been developed by the FAA. The estimates of economic impacts for the final rule revisions have been constructed from unit cost and other data obtained from air carriers, industry trade associations, and manufacturers.

Information for analysis of benefits was obtained from the safety records of the NTSB and the FAA. The costs calculated for these amendments have been projected over the 16-year period of 1989 to 2004. This analysis compares these costs to benefits accruing over the 15-year span of 1990 to 2004. The purpose of this is to account for the fact that in 1989, the first year after the rule is published, no airplanes equipped with the required avionics will be in service. In 1989, however, impacted entities will incur program and planning start-up costs.

In the Notice of Proposed Rulemaking (NPRM), the FAA invited public comments concerning the technical and operational considerations and economic impact assumptions as these apply to flight guidance systems equipment modification and replacement, the frequency and duration of Part 121 certificate holder's windshear simulator flight training, and the extent to which Part 135 operators provide instruction to their pilots in procedures to recognize and escape inadvertent encounters with low-altitude windshear. Comments on the proposal were submitted by individuals, foreign and domestic air carriers, air carrier and airline pilot associations, avionics manufacturers, and the National Transportation Safety Board. The majority of comments commended the FAA for taking action to reduce the hazards of windshear encounters. A number of commenters, however, opposed certain proposed requirements and disagreed with economic impact estimates presented in the proposal. The FAA has evaluated the public comments and made the final determination regarding their impact. The comments have caused the FAA to revise its analysis and increase compliance costs.

A substantial change in the final rule is the provision of a time-phased retrofit schedule for airborne windshear equipment requirements. The final rule requires compliance by 2 years after the effective date of the final rule for all airborne equipment requirements unless an operator submits a schedule to show phased compliance over a 4-year period from the effective date of the rule. Under § 121.358(b) at least 50 percent of a certificate holder's airplanes that were manufactured before the effective date of the rule must be retrofitted within 2 years, at least 25 percent more within 3 years, and the remainder of airplanes affected within 4 years. The final rule also established that the ground and flight training provisions of the rule will take effect two years after the effective date of the rule. The time permitted for

compliance with the ground and flight training requirements will allow certificate holders sufficient time to train flight crews and convert simulators in advance of the compliance date for the required airborne windshear warning and flight guidance equipment. The FAA believes that the time allowed for training and equipment installation and modification will reduce costs and facilitate compliance.

The FAA finds that with the exception of new § 121.358 and the amendments to §§ 121.407, 121.409, 121.424, and 121.427, the amendments affecting Part 121 operators will have a negligible cost or no cost impact. The FAA has also determined the cost of compliance with the upgraded testing and training requirements of the amendments to §§ 135.293, 135.345, and 135.351 to be minimal.

New § 121.358 and the amendments §§ 121.407, 121.424, and 121.427 have been analyzed independently. For the purpose of this evaluation, however, the costs associated with these revisions have been aggregated. The reason is that these amendments are inextricably related and share the common objective of improving the skills of pilots in recognizing and escaping from inadvertently encountered low-altitude windshear conditions.

New § 121.358 will have an economic impact on the approximate 3,800 airplanes expected to be in service in 1990 and 3,200 airplanes expected to be manufactured between 1991 and 2004 because they would be required to be equipped with an FAA-approved system providing airborne windshear warning and flight guidance. The estimated cost of this amendment is \$372.2 million in 1987 dollars and \$218.5 million at a present worth discount rate of 10 percent over the 16-year period of 1989 to 2004.

The amendment to § 121.407 would require that air carriers install approved windshear aerodynamic data programs in their flight simulators. The estimated cost of modifying the 150 flight simulators currently in use by Part 121 certificate holders is \$6.2 million in 1987 dollars.

The cost per hour of additional simulator utilization has been estimated under § 121.409 and added to the time captains and first officers would spend in a flight simulator to comply with the windshear simulator flight training requirements of §§ 121.424 and 121.427.

The FAA has determined that approximately 80 percent of the affected certificate holders already provide the windshear flight training required by §§ 121.424 and 121.427. Therefore, the amendments to these sections would

impact approximately 20 percent of the active and future captains and first officers of the 149 Part 121 certificate holders affected by the rule. The estimated cost of compliance with the initial, transition, and upgrade windshear flight simulator training requirements of § 121.424 would be \$13.4 million in 1987 dollars and \$7.1 million when discounted at 10 percent over the 15-year span between 1989 and 2004. The estimated cost of requiring the affected captains and first officers to undergo windshear simulator flight training pursuant to the recurrent training requirements specified in § 121.427 would be \$33.8 million in 1987 dollars and \$15.2 million at a present worth discount rate of 10 percent over the same time period.

This analysis indicates that the total cost of compliance with the equipment acquisition, installation, maintenance and flight training requirements contained in this rule is estimated to have a present value of \$246.5 million over the 16 year-period of 1989 to 2004.

To estimate the benefits for the NPRM, the FAA examined the safety record of Part 121 air carriers for the 15-year period between 1971 and 1985. At the time, this review indicated that 15 accidents attributed to windshear phenomena occurred during this period. A more recent review, however, reveals that two more accidents attributed to windshear have been added to the safety record by the NTSB for the same 15-year period in question. Accordingly, the losses associated with the 17 accidents are the basis for the benefits of this rule. Moreover, the analysis has been advanced to reflect the more recent 15-year period of 1972 to 1986.

To arrive at a loss rate indicative of the cost of these accidents, the total financial loss of these accidents was divided into the total number of turbine-powered airplane air carrier operations for the same 15-year period of 1972 to 1986. This calculation established a loss rate of \$4.34 per turbine-powered air carrier operation over the 15-year period of 1972 to 1986. Similarly, to estimate the future accident prevention value of this rule, the established loss rate was multiplied by the number of operations forecast for the 15 years from 1990 to 2004. This calculation reveals that the estimated potential discounted benefit associated with the prevention of casualty loss in accidents attributed to windshear to be \$451.6 million.

The FAA has been unable to quantitatively estimate the accident prevention effectiveness of these amendments. The total discounted cost of compliance of these amendments can be fully recovered if the rule is only 55

percent effective in reducing future casualty loss. The FAA believes that enactment of these amendments will significantly reduce the number of future windshear incidents and accidents and that benefits will exceed costs.

This regulatory evaluation focused on the rulemaking it supported. There are other programs which are also designed to reduce the risk of windshear accidents. These other programs are justified partially by benefits included in this analysis, and additional benefits over and above those necessary to justify the rulemaking. FAA does not believe this rulemaking would eliminate or reduce the need for other programs such as terminal Doppler weather radar and Low-Level Wind Shear Alert Systems.

#### Regulatory Flexibility Determination

The Regulatory Flexibility Act of 1980 requires a review of rules to assess their impact on small business. The required Part 121 amendments will have a significant economic impact on a substantial number of small entities. However, the FAA finds that there are no viable alternatives for small air carriers to adopt that would reduce the cost of compliance yet achieve the level of protection sought by this rulemaking. The amendments to part 135 have been determined to impose only minimal costs. Therefore, Part 135 certificate holders would not incur a significant economic impact as a result of these amendments.

#### International Trade Impact Statement

These amendments will have little or no impact on trade opportunities of United States firms doing business overseas or for foreign firms doing business in the United States. These amendments apply only to Part 121 and Part 135 certificate holders and assign responsibility for the provision of the required equipment and windshear training programs specified in the rule to the operating certificate holder. Because most Part 121 and Part 135 certificate holders compete domestically for passenger and cargo revenues with other U.S. operators, this rule will not cause a competitive fare disadvantage for U.S. carriers.

#### Federalism Implications

The regulations herein would not have substantial direct effects on the states, on the relationship between the National government and the states, or on the distribution of power and responsibilities among the various levels of government. Thus, in accordance with Executive Order 12612, it is determined

that these regulations do not have federalism implications requiring the preparation of a Federalism Assessment.

#### Paperwork Reduction Act Approval

The recordkeeping and reporting requirements contained in this final rule (§ 121.358) have been submitted to the Office of Management and Budget for review since these provisions were not included in the notice of proposed rulemaking. Comments on these requirements should be submitted to the Office of Information and Regulatory Affairs (OMB), New Executive Office Building, Room 3001, Washington, DC 20503, Attention: FAA Desk Officer (Telephone 202-395-7340). A copy should be submitted to the FAA docket.

#### Conclusion

The FAA has determined that this amendment is not major under Executive Order 12291 but that it is significant under the Department of Transportation Regulatory Policies and Procedures (44 FR 11034, February 26, 1979). For the reasons discussed above, it also has been determined that the amendments to Part 121 will have a significant economic impact on a substantial number of small entities, but that the amendments to Part 135 will not have a significant economic impact on a substantial number of small entities.

#### List of Subjects

##### 14 CFR Part 121

Air carriers, Air transportation, Aviation safety, Common carriers, Safety, Transportation, Windshear.

##### 14 CFR Part 135

Air carriers, Air taxi, Air transportation, Aviation safety, Safety, Windshear.

#### The Rule

Accordingly, the Federal Aviation Administration amends Parts 121 and 135 of the Federal Aviation Regulations (14 CFR Parts 121 and 135) as follows:

#### PART 121—CERTIFICATION AND OPERATIONS: DOMESTIC, FLAG, AND SUPPLEMENTAL AIR CARRIERS AND COMMERCIAL OPERATORS OF LARGE AIRCRAFT

1. The authority citation for Part 121 continues to read as follows:

Authority: 49 U.S.C. 1354(a), 1355, 1356, 1357, 1401, 1421-1430, 1472, 1485, and 1502; 49 U.S.C. 106(g) (Revised, Pub. L. 97-448, January 12, 1983).

2. By adding a new § 121.358 to read as follows:

#### § 121.358 Low-altitude windshear system equipment requirements.

(a) Except as provided in paragraph (b) of this section, after January 2, 1991, no person may operate a turbine-powered airplane unless it is equipped with an approved system providing airborne windshear warning with flight guidance. For the purpose of this section, "turbine-powered airplane" includes, e.g., turbofan-, turbojet-, propfan-, and ultra-high bypass fan-powered airplanes. The definition specifically excludes turbopropeller-powered airplanes with variable pitch propellers with constant speed controls.

(b) A certificate holder may obtain an extension of the compliance date in paragraph (a) of this section for airplanes manufactured before January 2, 1989 if it obtains FAA approval of a retrofit schedule. For the purposes of this section, an airplane is considered manufactured on the date the inspection acceptance records reflect that the airplane is complete and meets the FAA Approved Type Design Data. To obtain approval of a retrofit schedule and show continued compliance with that schedule, a certificate holder must do the following:

(1) Submit a request for approval of a retrofit schedule by June 1, 1990 to the Flight Standards Division Manager in the region of the certificate holding district office. Final approval will be granted by the Director of Flight Standards (AFS-1).

(2) Show, for those airplanes subject to this section that are listed in the certificate holder's maintenance operations specifications on the date that the request for extension is submitted, that at least 50% of those airplanes manufactured before January 2, 1989 will be equipped by January 2, 1991, at least 25% more of those airplanes by January 2, 1992, and all of the certificate holder's airplanes required to be equipped in accordance with this section by January 4, 1993.

(3) Comply with its retrofit schedule and submit status reports containing information acceptable to the Administrator. The initial report must be submitted by January 2, 1991, and subsequent reports must be submitted every six months thereafter until completion of the schedule. The reports must be submitted to the FAA Flight Standards District Office charged with the overall inspection of the certificate holder's operations.

3. By adding a new § 121.404 to read as follows:

#### § 121.404 Windshear training: Compliance dates.

After January 2, 1991, no certificate holder may use a person as a flight crewmember unless that person has completed—

(a) Windshear ground training in accordance with § 121.419 of this part.

(b) Windshear flight training, if applicable, in accordance with §§ 121.409, 121.424, and 121.427 of this part.

4. By amending § 121.407 by adding a new paragraph (d) to read as follows:

#### § 121.407 Training program: Approval of airplane simulators and other training devices.

(d) An airplane simulator approved under this section must be used instead of the airplane to satisfy the pilot flight training requirements prescribed in the certificate holder's approved low-altitude windshear flight training program set forth in § 121.409(d) of this part.

5. By amending § 121.409 by adding a new paragraph (d) to read as follows:

#### § 121.409 Training courses using airplane simulators and other training devices.

(d) Each certificate holder required to comply with § 121.358 of this part must use an approved simulator for each airplane type in each of its pilot training courses that provides training in at least the procedures and maneuvers set forth in the certificate holder's approved low-altitude windshear flight training program. The approved low-altitude windshear flight training, if applicable, must be included in each of the pilot flight training courses prescribed in §§ 121.409(b), 121.418, 121.424, and 121.427 of this part.

6. By amending § 121.419 by revising paragraph (a)(2)(vi) to read as follows:

#### § 121.419 Pilots and flight engineers: Initial, transition, and upgrade ground training.

(a) . . .

(2) . . .

(vi) Procedures for—

(A) Recognizing and avoiding severe weather situations;

(B) Escaping from severe weather situations, in case of inadvertent encounters, including low-altitude windshear, and

(C) Operating in or near thunderstorms (including best penetrating altitudes), turbulent air (including clear air turbulence), icing, hail, and other potentially hazardous meteorological conditions;



7. By amending § 121.424 by revising paragraphs (a), (b), and (d) to read as follows:

**§ 121.424 Pilots: Initial, transition, and upgrade flight training.**

(a) Initial, transition, and upgrade training for pilots must include flight training and practice in the maneuvers and procedures set forth in the certificate holder's approved low-altitude windshear flight training program and in Appendix E to this part, as applicable.

(b) The maneuvers and procedures required by paragraph (a) of this section must be performed inflight except—

(1) That windshear maneuvers and procedures must be performed in a simulator in which the maneuvers and procedures are specifically authorized to be accomplished; and

(2) To the extent that certain other maneuvers and procedures may be performed in an airplane simulator, an appropriate training device, or a static airplane as permitted in Appendix E to this part.

(d) If the certificate holder's approved training program includes a course of training utilizing an airplane simulator under § 121.409 (c) and (d) of this part, each pilot must successfully complete—

(1) With respect to § 121.409(c) of this part—

(i) Training and practice in the simulator in at least all of the maneuvers and procedures set forth in Appendix E to this part for initial flight training that are capable of being performed in an airplane simulator without a visual system; and

(ii) A flight check in the simulator or the airplane to the level of proficiency of a pilot in command or second in command, as applicable, in at least the maneuvers and procedures set forth in Appendix F to this part that are capable of being performed in an airplane simulator without a visual system.

(2) With respect to § 121.409(d) of this part, training and practice in at least the maneuvers and procedures set forth in the certificate holder's approved low-altitude windshear flight training program that are capable of being performed in an airplane simulator in which the maneuvers and procedures are specifically authorized.

8. By amending § 121.427 by revising the introductory text of paragraph (d)(1) to read as follows:

**§ 121.427 Recurrent training.**

(d) . . .

(1) For pilots, flight training in an approved simulator in maneuvers and

procedures set forth in the certificate holder's approved low-altitude windshear flight training program and flight training in maneuvers and procedures set forth in Appendix F to this part, or in a flight training program approved by the Administrator, except as follows—

9. By amending § 121.433 by revising paragraph (c)(2) and adding a new paragraph (e) to read as follows:

**§ 121.433 Training required.**

(c) . . .

(2) For pilots, a proficiency check as provided in § 121.441 of this part may be substituted for the recurrent flight training required by this paragraph and the approved simulator course of training under § 121.409(b) of this part may be substituted for alternate periods of recurrent flight training required in that airplane, except as provided in paragraphs (d) and (e) of this section.

(e) Notwithstanding paragraphs (c)(2) and (d) of this section, a proficiency check as provided in § 121.441 of this part may not be substituted for training in those maneuvers and procedures set forth in a certificate holder's approved low-altitude windshear flight training program when that program is included in a recurrent flight training course as required by § 121.409(d) of this part.

10. By amending Part 121, Appendix E by revising the first paragraph to read as follows:

**Appendix E—Flight Training Requirements**

The maneuvers and procedures required by § 121.424 of this part for pilot initial, transition, and upgrade flight training are set forth in the certificate holder's approved low-altitude windshear flight training program and in this appendix and must be performed inflight except that windshear maneuvers and procedures must be performed in an airplane simulator in which the maneuvers and procedures are specifically authorized to be accomplished and except to the extent that certain other maneuvers and procedures may be performed in an airplane simulator with a visual system (visual simulator), an airplane simulator without a visual system (nonvisual simulator), a training device, or a static airplane as indicated by the appropriate symbol in the respective column opposite the maneuver or procedure.

**PART 135—AIR TAXI OPERATORS AND COMMERCIAL OPERATORS**

11. The authority citation for Part 135 continues to read as follows:

Authority: 49 U.S.C. 1354(a), 1355(a), 1421 through 1431, and 1502; 49 U.S.C. 106(g) (Revised Pub. L. 97-449, January 12, 1983).

12. By revising § 135.10 to read as follows:

**§ 135.10 Compliance dates for certain rules.**

After January 2, 1991, no certificate holder may use a person as a flight crewmember unless that person has completed the windshear ground training required by §§ 135.345(b)(6) and 135.351(b)(2) of this part.

13. By amending § 135.293 by revising paragraph (a)(7) to read as follows:

**§ 135.293 Initial and recurrent pilot testing requirements.**

(a) . . .

(7) Procedures for—

(i) Recognizing and avoiding severe weather situations;

(ii) Escaping from severe weather situations, in case of inadvertent encounters, including low-altitude windshear (except that rotorcraft pilots are not required to be tested on escaping from low-altitude windshear); and

(iii) Operating in or near thunderstorms (including best penetrating altitudes), turbulent air (including clear air turbulence), icing, hail, and other potentially hazardous meteorological conditions; and

14. By amending § 135.345 by revising paragraph (b)(6) to read as follows:

**§ 135.345 Pilots: Initial, transition, and upgrade ground training.**

(b) . . .

(6) Procedures for—

(i) Recognizing and avoiding severe weather situations;

(ii) Escaping from severe weather situations, in case of inadvertent encounters, including low-altitude windshear (except that rotorcraft pilots are not required to be trained in escaping from low-altitude windshear); and

(iii) Operating in or near thunderstorms (including best penetrating altitudes), turbulent air (including clear air turbulence), icing, hail, and other potentially hazardous meteorological conditions;

15. By amending § 135.351 by revising paragraph (b)(2) to read as follows:

§ 135.351 Recurrent training.

(b) . . .

(2) Instruction as necessary in the subjects required for initial ground training by this subpart, as appropriate, including low-altitude windshear training as prescribed in § 135.345 of this part and emergency training.

Issued in Washington, DC, on September 22, 1988.

T. Allan McArtor,  
*Administrator.*

[FR Doc. 88-22088 Filed 9-22-88 4:58 pm]

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## **Session I. Airborne—Terms of Reference**

Flight Experience with Wind Shear Detection  
Terry Zweifel, Honeywell/Sperry

**NASA**

**SECOND COMBINED MANUFACTURERS' AND TECHNOLOGY  
AIRBORNE WINDSHEAR REVIEW MEETING**

**OCTOBER 18 - 20, 1988  
WILLIAMSBURG, VIRGINIA**

**FLIGHT EXPERIENCE  
WITH WINDSHEAR DETECTION**

**PRESENTED BY:**

**TERRY ZWEIFEL**

**HONEYWELL INC.  
SPERRY COMMERCIAL FLIGHT SYSTEMS GROUP  
PHOENIX, ARIZONA**

527390  
N91-11684  
FLIGHT EXPERIENCE WITH  
WINDSHEAR DETECTION

Terry Zweifel  
Honeywell Corporation  
Phoenix, Arizona

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ABSTRACT

Windshear alerts resulting from the Honeywell Windshear Detection and Guidance System are presented based on data from approximately 248,000 revenue flights at Piedmont Airlines. The data indicate that the detection system provides a significant benefit to the flight crew of the aircraft. In addition, nuisance and false alerts were found to occur at an acceptably low rate to maintain flight crew confidence in the system. Data from a digital flight recorder is also presented which shows the maximum and minimum windshear magnitudes recorded for a representative number of flights in February, 1987. The effect of the boundary layer of a steady state wind is also discussed.

INTRODUCTION

The Honeywell Corporation has developed a Windshear Detection and Guidance System which is currently in use by Piedmont Airlines on their Boeing 737-200 aircraft fleet.

The detection and guidance system consists of air data information, inertial sensors, and software algorithms resident in Honeywell's Performance Management System.

Certification of the system by the Federal Aviation Administration consisted of two phases. The first phase was the certification of the detection portion of the system. This was accomplished in November 1985. The second phase was certification of the guidance algorithms, and was completed in December 1986. The partitioning of the certification was deliberate: by getting a detection system out in the field as quickly as possible, a substantial amount of data could be gathered in parallel with the design and development of the guidance control laws. Consequently, modifications and refinements to the detection algorithm could be, and were, made.

The improved detection algorithm was released for service in September, 1986. Guidance algorithms were included during the first part of 1987. This paper presents an analysis of the detection algorithm performance during approximately 248,000 flights.

METHODS OF DATA GATHERING

Three separate methods of data gathering were utilized during the evaluation:

1. Discrete and max/min parameter storage in non-volatile memory.

2. Digital recording of 26 parameters in real time.
3. Pilot reporting using a standardized form.

The Windshear Detection and Guidance System has the capability of storing 49 internal parameters in non-volatile memory. Periodically, the data were read out by maintenance personnel servicing the aircraft. These data were primarily used in the early stages of algorithm evaluation to modify and refine the detection software. While the data are still recorded, it is an overwhelming logistics task to read and record data from a fleet of 62 aircraft. The data is also necessarily limited to one-time reading of digital data words; that is, only parameters for a unique aircraft state can be stored with no time variance. This scheme also suffered from the possibility of human error in reading and recording the data.

The preferable method of retrieving data is through a digital flight recorder capable of recording data at a one second rate. This scheme was used on all the certification flights, and is currently used aboard one aircraft. A total of 26 parameters, including relevant aircraft data such as speed, altitude and pitch angle, are recorded during the time the Windshear Detection and Guidance System is active (takeoff, landing approach, and go around). The data are useful in deriving peak g-levels (energy rates) of windshear that the aircraft experiences as well as confirming proper algorithm performance. Ideally, one would like such a recorder on all aircraft. Unfortunately, this is not very practical. Aside from the economics of equipping all aircraft with such a recorder, the data analysis of a large number of flights would tax the resources of even a large engineering department.

The third source of data relies on pilot reporting of windshear alerts produced by the system. A sample form is shown in Figure 1. While parametric data is not available, it has the advantage of being a very direct measure of system acceptance by the flight crew. Other useful data includes the date and location of the occurrence, general weather conditions, and ATC advisories. The location of the occurrence is particularly meaningful since certain airports are known to have windshears produced by the surrounding terrain. Aside from not being able to determine the exact magnitude of the encountered windshear, one must also rely on a busy flight crew already encumbered by necessary paperwork to report system annunciations.

#### DIGITAL FLIGHT RECORDER DATA

In order to assess the windshear environment, data from the digital flight recorder was compiled for 50 flights that occurred in early February, 1987. For each flight regime, i.e.,

takeoff and landing approach, the maxima and minima windshear magnitudes were recorded. The data are essentially raw data with the exception of a one second low pass filter used to attenuate noise from the required differentiator. Figures 2 and 3 illustrate typical time histories.

It should be pointed out that none of the flights experienced a significant windshear event. Even though relatively large values of windshear occurred, the windshear was not sustained long enough to seriously degrade the aircraft's performance and all flights proceeded routinely.

A compendium of the data is presented in histogram form on Figures 4 through 7. Figures 4 and 5 illustrate longitudinal windshear magnitudes seen in landing approach and takeoff respectively. Figures 6 and 7 illustrate the encountered vertical winds measured in feet per second. While the landing approach data appears to be fairly Gaussian in nature, an examination of the takeoff data indicates a slight positive bias.

A steady state wind will produce a boundary layer near the ground. As the magnitude of the wind in the boundary layer is a function of altitude, an effective windshear field is produced. Any aircraft flying through the boundary layer will experience a windshear. The magnitude of the shear experienced will be a function of the altitude rate of the aircraft. As most takeoffs and landing approaches are made into the prevailing wind, an aircraft on takeoff could experience a headwind shear while an aircraft on landing approach could experience a tailwind shear due to the boundary layer. Figures 8 and 9 illustrate the actual phenomenon. In Figure 8, the aircraft took off into a prevailing headwind while in Figure 9 a tailwind was present. In both cases, a high sensitivity detection system would have, and did, measure a windshear. The effect is most pronounced in takeoff since the altitude rate of the aircraft can be large. Most landing approaches are done at much lower altitude rates, typically -10 feet per second (-3 meters/sec). Consequently, one would expect the magnitude of the windshear caused by the boundary layer to be larger takeoff than in landing approach. It is this effect which causes the bias noted in the takeoff data.

#### RESULTS OF THE WINDSHEAR EVALUATION FORMS

As of the time of this writing, approximately 248,000 revenue flights have been flown with the latest configuration of the Honeywell Windshear Detection and Guidance System. Twelve Windshear Evaluation Forms indicating the occurrence of a windshear alert have been received from the flight crews. The results are tabulated in Table 1:

TABLE 1

## WINDSHEAR ALERT DATA

DATE	AIRPORT	FLIGHT REGIME	ALERT TYPE	ATC ALERT?
11 Apr 87	Fayetteville, NC	Takeoff	Warning	No
4 May 87	Dayton, OH	Landing	Warning	No
6 Jun 87	Charleston, WV	Landing	Caution	No
10 Jun 87	Baltimore, MD	Landing	Warning	No
28 Jun 87	Charlotte, NC	Takeoff	Warning	No
19 Jul 87	Charlotte, NC	Landing	Warning	No
9 Aug 87	Orlando, FL	Takeoff	Warning	No
26 Aug 87	Dallas, TX	Takeoff	Warning	No
29 Dec 87	Charlotte, NC	Landing	Warning	Yes
29 Dec 87	Roanoke, VA	Landing	Warning	Yes
23 Apr 88	Buffalo, NY	Takeoff	Warning	-
15 May 88	Dayton, OH	Landing	Warning	Yes

The alert type in the table refers to whether the alert was for an increasing headwind or updraft, a caution alert, or for a decreasing tailwind or downdraft, a warning alert. The ATC alert column indicates whether the flight crew was advised by Air Traffic Control of potential windshears at the airport.

The Federal Aviation Administration has defined windshear alerts as falling into three categories. The first is a valid alert wherein the windshear has seriously degraded the performance capability of the aircraft. The second is a nuisance alert where an actual windshear occurs, but its magnitude and duration are not sufficient to endanger the aircraft. The third category is the false alert where an alert occurs in the absence of a windshear condition.

The alerts of 28 Jul 87 and 9 Aug 87 were false alerts caused by an undetected sensor failure and a computer failure respectively. Subsequent modifications to the built-in-test software should preclude reoccurrence.

Of the remaining ten reports, six are valid alerts substantiated by the flight crew. At least four of these are believed to be microburst encounters: 4 May 87, 26 Aug 87, 23 Apr 88, and 15 May 88. In all cases, the aircraft successfully exited the windshear using the Windshear Detection and Guidance System.

The remaining four are classified in the nuisance category. Nuisance alerts can occur due to two causes: (a) terrain-induced shears, and (b) gusts of sufficient magnitude and duration to cause a relatively short-term performance loss. Two of the occurrences, 6 Jun 87 and 10 Jun 87 are believed to be the result of terrain-induced windshears as the airports are known to have such properties. The cause of the remaining two is believed to be gust-induced.

Using a base of 248,000 flights and the data from Table 1, Table 2 can be produced:

TABLE 2

## PROBABILITY OF WINDSHEAR ALERTS

EVENT	PROBABILITY ( $10^{-5}$ )	NUMBER IN X FLIGHTS
All Alerts	4.8	1 in 20,667
Valid Alert	2.4	1 in 41,333
Nuisance Alert	1.6	1 in 62,000
False Alert	0.8	1 in 124,000

Figure 10 illustrates the occurrence of windshears by calendar month. The two false alerts have been excluded. With the exception of the December data, the occurrence of an alert is most probable in the spring and summer months when thunderstorms are more prevalent. The data agree in general with the data from other microburst windshear studies where windshears were found to be most common in warm months.

### CONCLUSIONS

The Honeywell Windshear Detection and Guidance System appears to provide timely windshear detection and, in at least two cases, has been credited by the flight crews as being of great benefit in successfully exiting an encountered windshear. Overall statistics indicate a windshear alert will occur once in 20,667 flights.

The occurrence of nuisance alerts, while acceptably low, is of some technical interest. To reduce nuisance alerts, sampling the atmosphere in terms of temperature and pressure may be needed. Such a sampling method could be used to compute the probability of a microburst and alter the detection algorithm threshold sensitivities accordingly. Studies are currently underway with both Piedmont and Delta airlines to assess the validity of such a method.

The number of false alerts is encouragingly low. Work has already been accomplished that should reduce the probabilities even further.

### ACKNOWLEDGEMENTS

The author would like to thank Piedmont Airlines and in particular Mr. Paul Gipson and Captain Jim Sifford for their cooperation in the development and testing of the Honeywell Windshear Detection and Guidance System and for making the data available that formed the basis of this paper.

PERFORMANCE MANAGEMENT SYSTEM  
WINDSHEAR EVALUATION FORM



This form must be completed any time a Windshear Caution or Warning advisory is activated automatically.

DATE \_\_\_\_\_ FLIGHT \_\_\_\_\_ ACFT. NO. \_\_\_\_\_ CAPTAIN \_\_\_\_\_

AIRPORTS \_\_\_\_\_ RUNWAY \_\_\_\_\_ CLG/VIS \_\_\_\_/\_\_\_\_ RVR \_\_\_\_\_ WINDS \_\_\_\_\_

TAKEOFF \_\_\_\_\_ ALTITUDE \_\_\_\_\_

FLAP SETTING \_\_\_\_\_

LANDING \_\_\_\_\_ ALTITUDE \_\_\_\_\_

FLAP SETTING \_\_\_\_\_

TYPE OF WARNING:

CAUTION \_\_\_\_\_

WARNING \_\_\_\_\_

WERE WINDSHEAR CONDITIONS REPORTED  
BY ATC? \_\_\_\_\_

OPINION:

FALSE \_\_\_\_\_ NUISANCE \_\_\_\_\_ VALID \_\_\_\_\_

APPROXIMATE LENGTH OF CAUTION/WARNING DURATION \_\_\_\_\_

GENERAL WEATHER CONDITIONS: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

MAIL TO AVIONICS ENGINEERING - A245

FIGURE 1



# W/S REVENUE SERVICE DATA

LD 4B 2/2/77

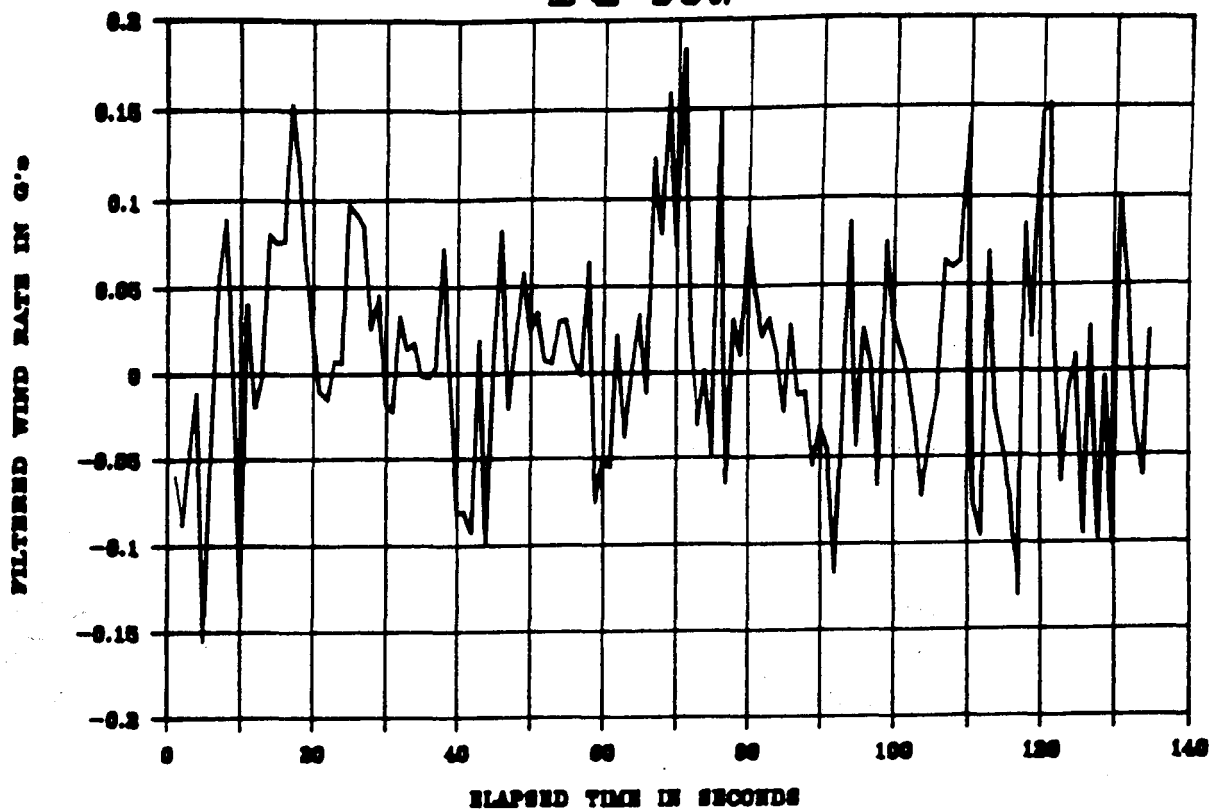


FIGURE 2

# W/S REVENUE SERVICE DATA

LD 14B 2/2/77

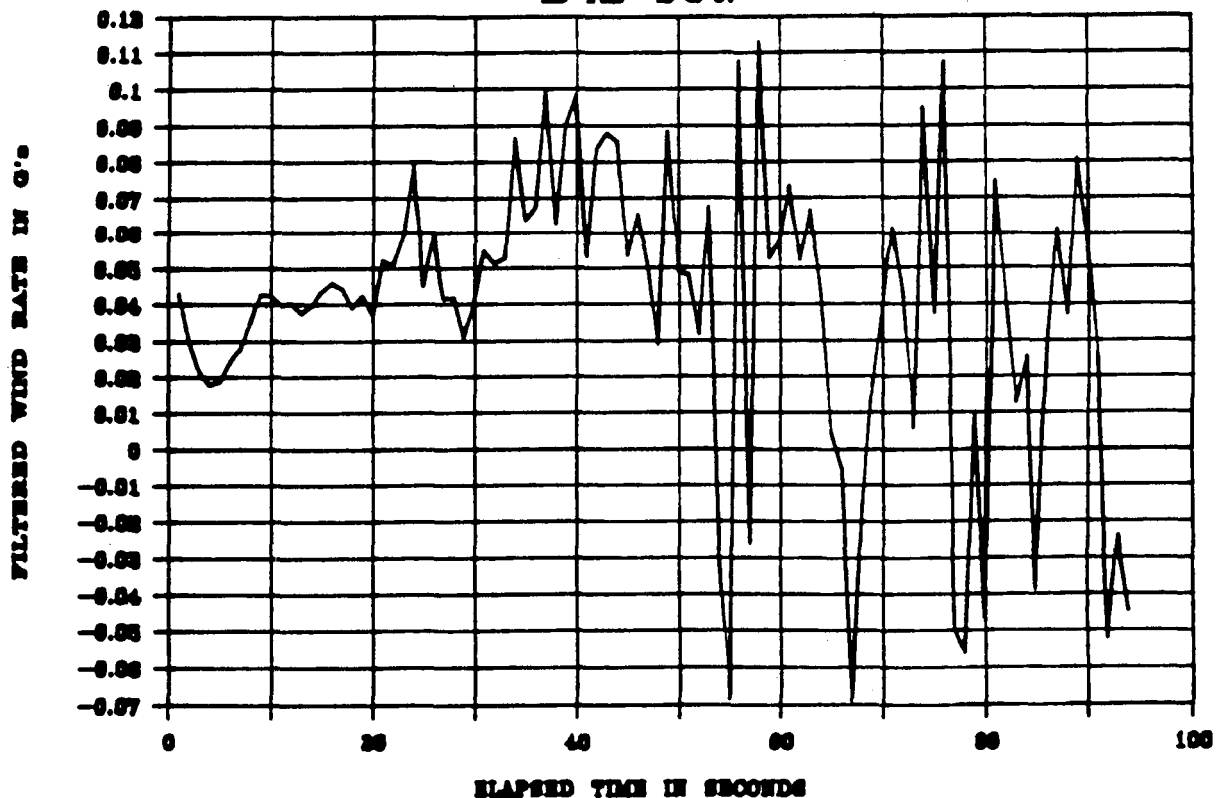


FIGURE 3

# W/S REVENUE SERVICE DATA

APPROACH MAX/MIN VALUES

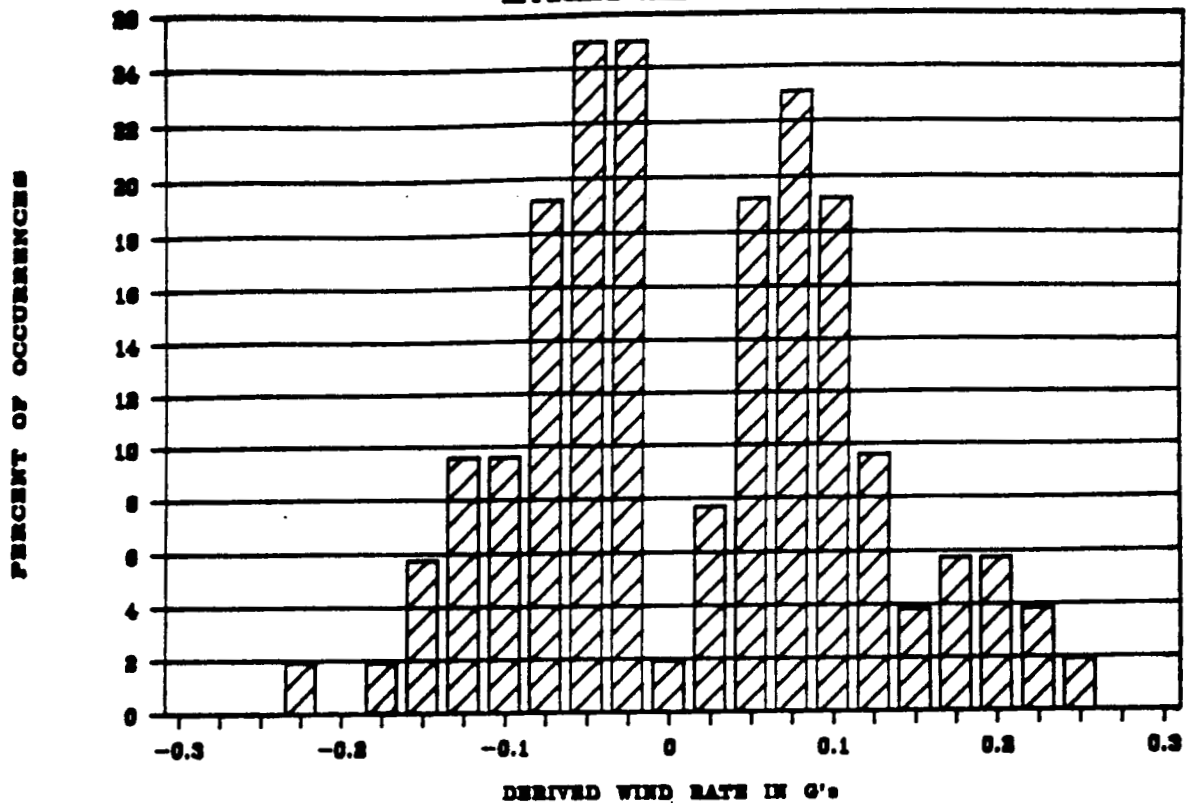


FIGURE 4

# W/S REVENUE SERVICE DATA

TAKEOFF MAX/MIN VALUES

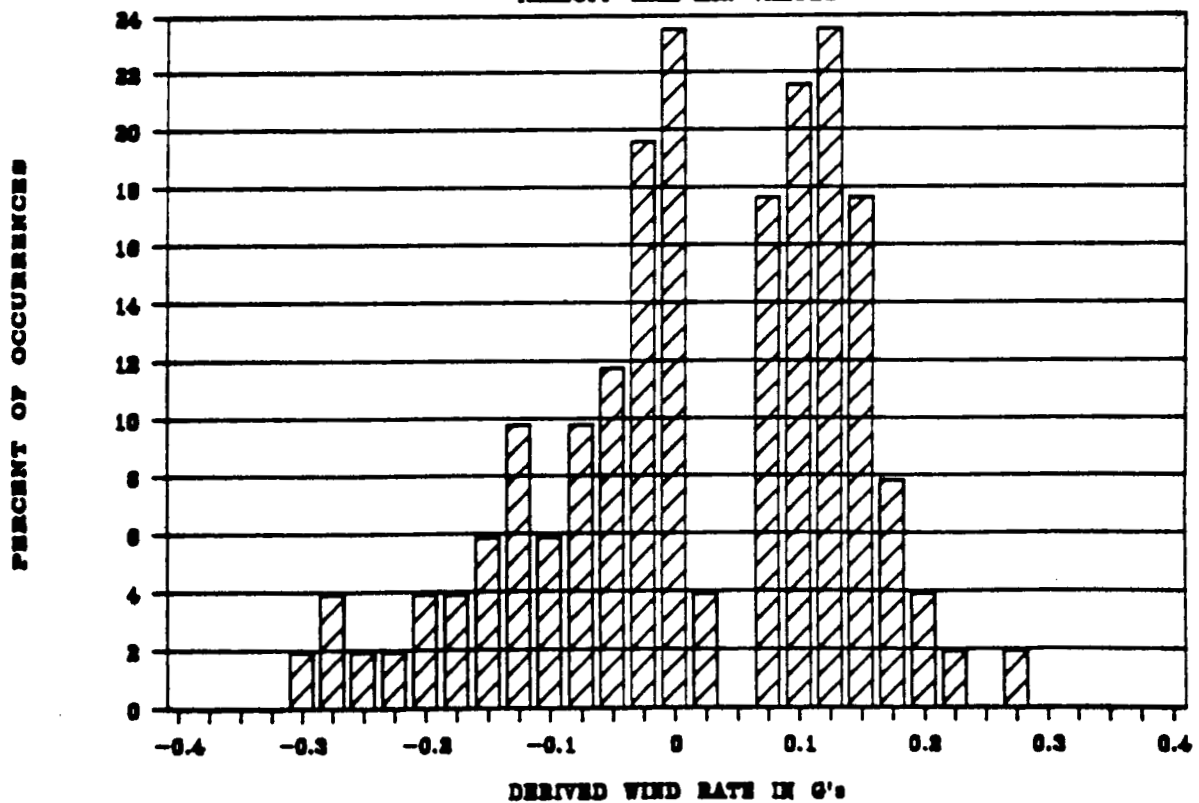


FIGURE 5

# W/S REVENUE SERVICE DATA

APPROACH MAX/MIN VALUES

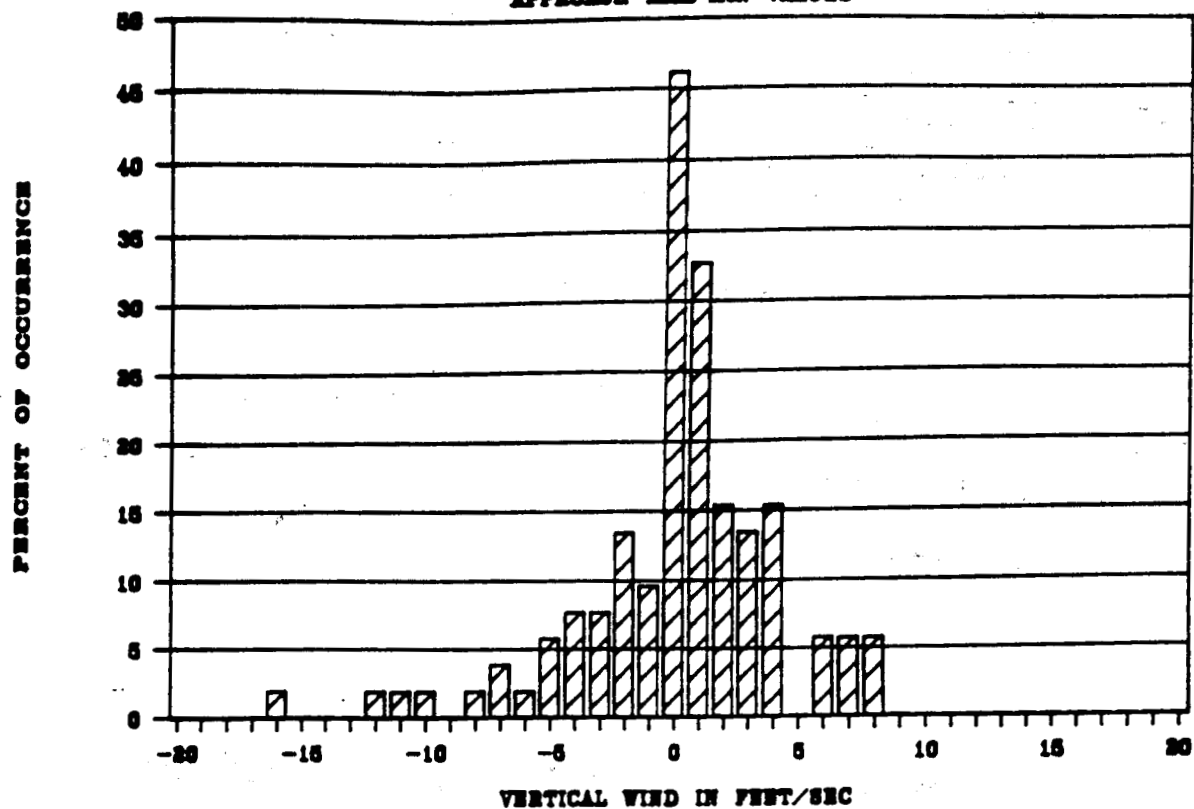


FIGURE 6

# W/S REVENUE SERVICE DATA

TAKEOFF MAX/MIN VALUES

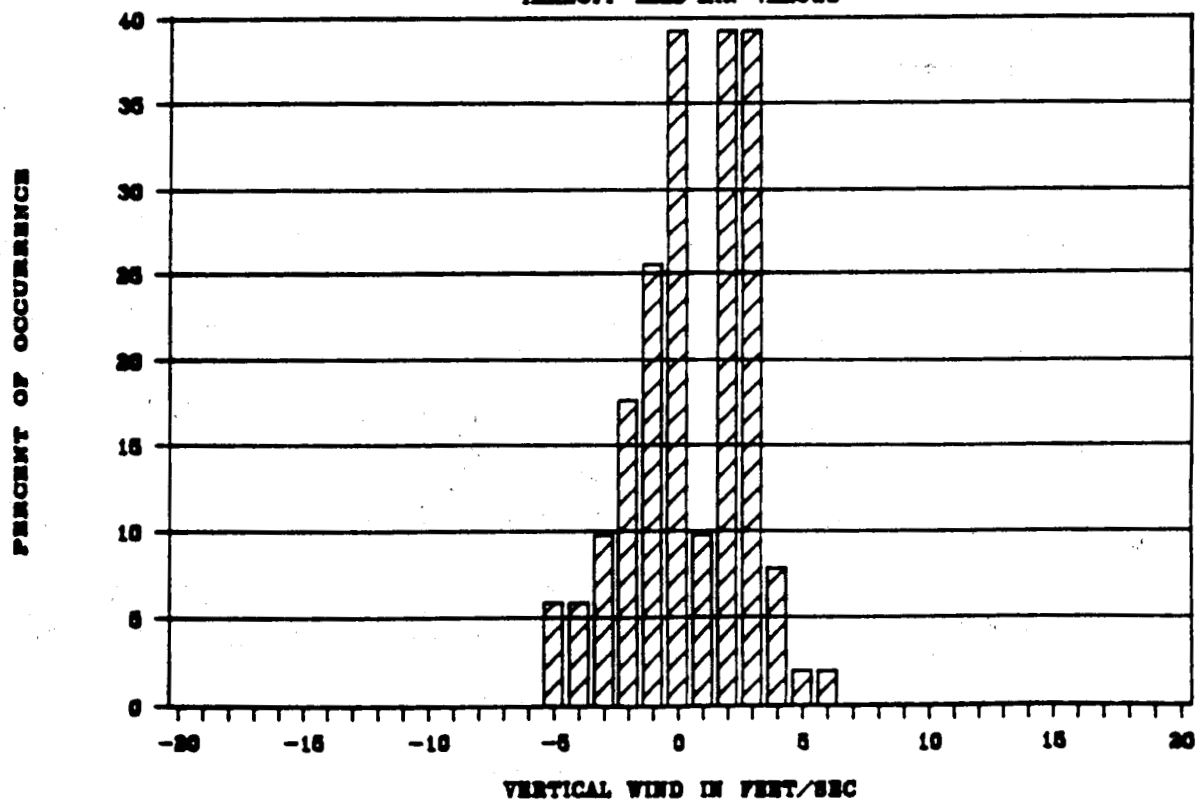


FIGURE 7

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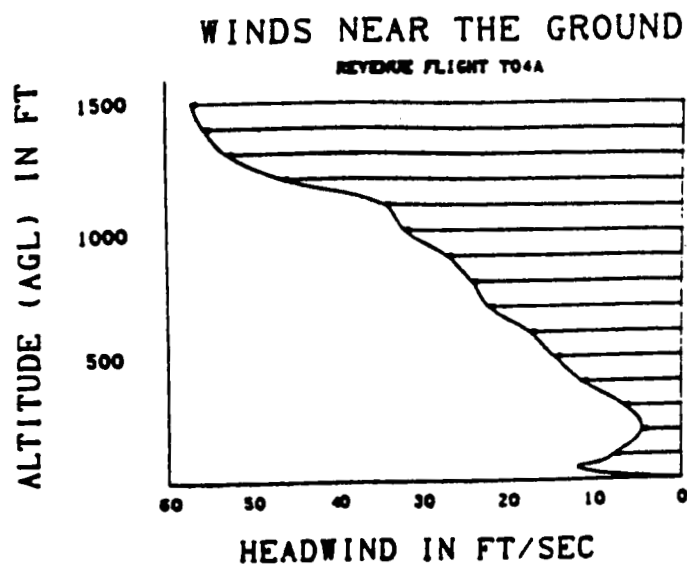


FIGURE 8

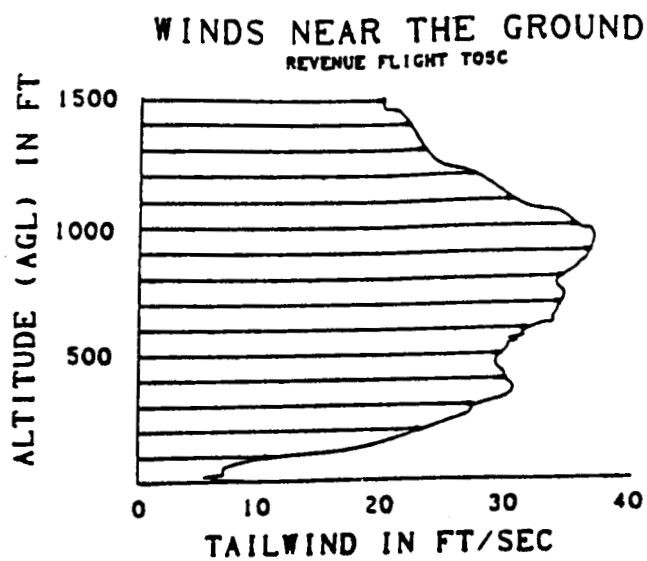


FIGURE 9

## WINDSHEAR ALERTS BY MONTH

SEP 87 - JUL 88

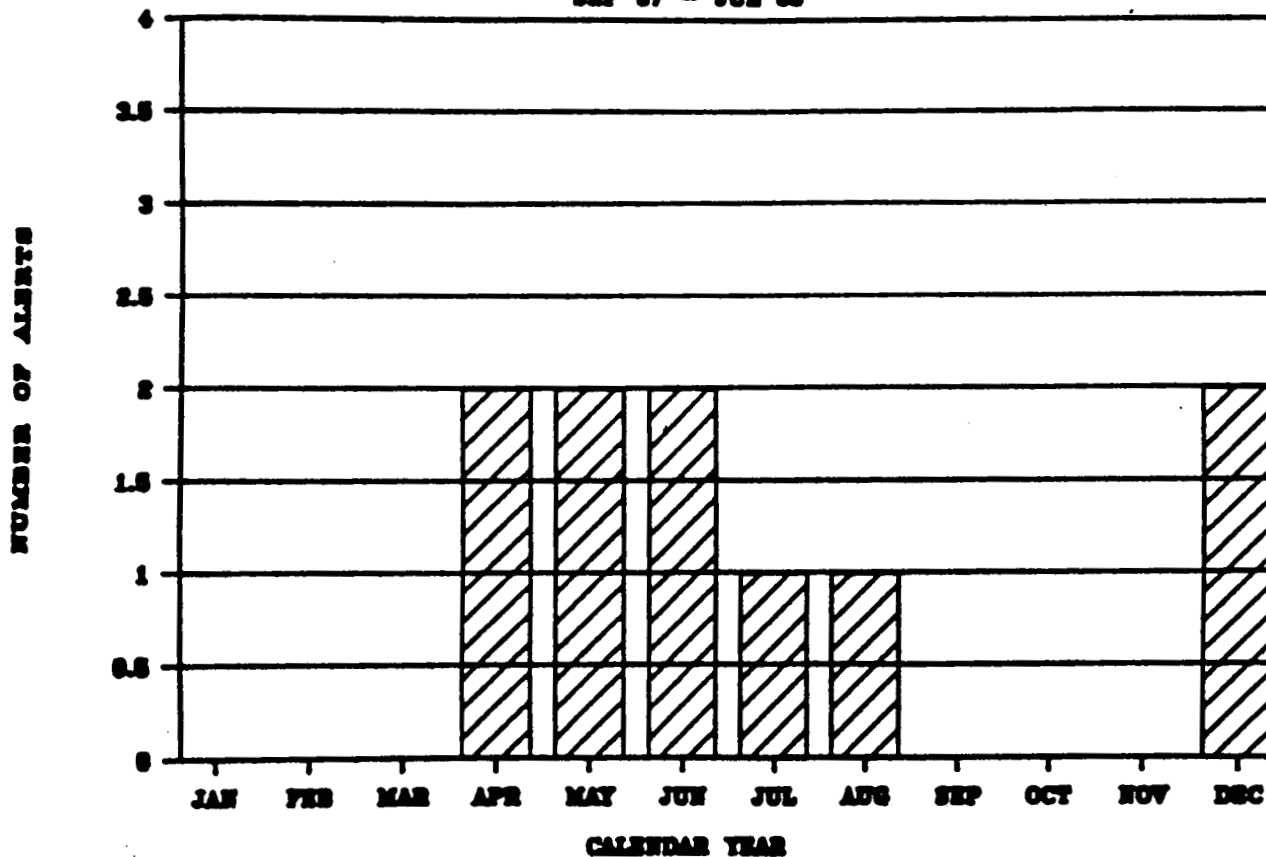


FIGURE 10

## **Session I. Airborne—Terms of Reference**

**Interface Standards for Integrated Forward-Looking Predictive/Reactive  
Wind Shear Systems  
Mark McGlinchey, Honeywell/Sperry**

**NASA**

**SECOND COMBINED MANUFACTURERS' AND TECHNOLOGY  
AIRBORNE WINDSHEAR REVIEW MEETING**

**OCTOBER 18 - 20, 1988  
WILLIAMSBURG, VIRGINIA**

**INTERFACE STANDARDS FOR INTEGRATED  
FORWARD-LOOKING/PREDICTIVE/REACTIVE  
WINDSHEAR SYSTEMS**

**PRESENTED BY:**

**MARK M. MCGLINCHEY**

**HONEYWELL INC.  
SPERRY COMMERCIAL FLIGHT SYSTEMS GROUP  
PHOENIX, ARIZONA**

**SLIDE NO. 1**

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INTERFACE STANDARDS FOR INTEGRATED  
FORWARD-LOOKING/PREDICTIVE/REACTIVE  
WINDSHEAR SYSTEMS

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## 1.0 ABSTRACT

Forward-looking windshear systems are developing to a point (particularly the infrared sensors) where their interface with the cockpit and reactive windshear systems needs to be defined. As airlines retrofit their aircraft with reactive windshear systems, it is important that we recognize that onboard windshear systems of the future will be a combination of both forward-looking and reactive elements. Today's reactive systems need to be built with the capability to interface to the forward-looking systems of tomorrow. This presentation is a first step at looking at the requirements and defining interface standards for integrated forward-looking and reactive windshear systems. Undoubtedly the requirements for interfacing these types of windshear systems will change as the technology changes.

## 2.0 DEFINITIONS

It is important that we communicate from a common baseline. Therefore, the definitions shown on Slide No. 2 will be used throughout this presentation. The important points to remember are:

- 1) Each type of windshear system performs a different task. Therefore, forward-looking systems are different from predictive systems which are different from reactive systems.
- 2) The caution and warning alerts are always controlled by the reactive system. Looking at the best failure modes for the total (forward-looking, predictive, and reactive) system, the forward or predictive systems should not operate without a reactive system. Yet, the reactive system must operate without the forward or predictive systems.

## 3.0 BLOCK DIAGRAM

What discussion of interfaces would be complete without the block diagram. As can be seen in Slide No. 3, the predictive and reactive systems can be combined into one LRU. Predictive elements (sensors and algorithms) can be readily incorporated into the reactive systems without the need for separate dedicated sensors or LRUs. The forward-looking and reactive/predictive systems will communicate over standard ARINC 429 data busses. The reactive/predictive system will supply the forward-looking system with data to help it perform its function. The forward-looking system will then supply the reactive/predictive system with data to activate the alerts or perform some precise threshold adjustment.

The forward-looking system will interface to a situational display which allows the flight crew to see the position of the event relative to the aircraft position or to display additional data (winds) concerning the event. It is foreseen that this would only be used by the flight crew when the aircraft was not in takeoff roll, takeoff, approach, or go-around.

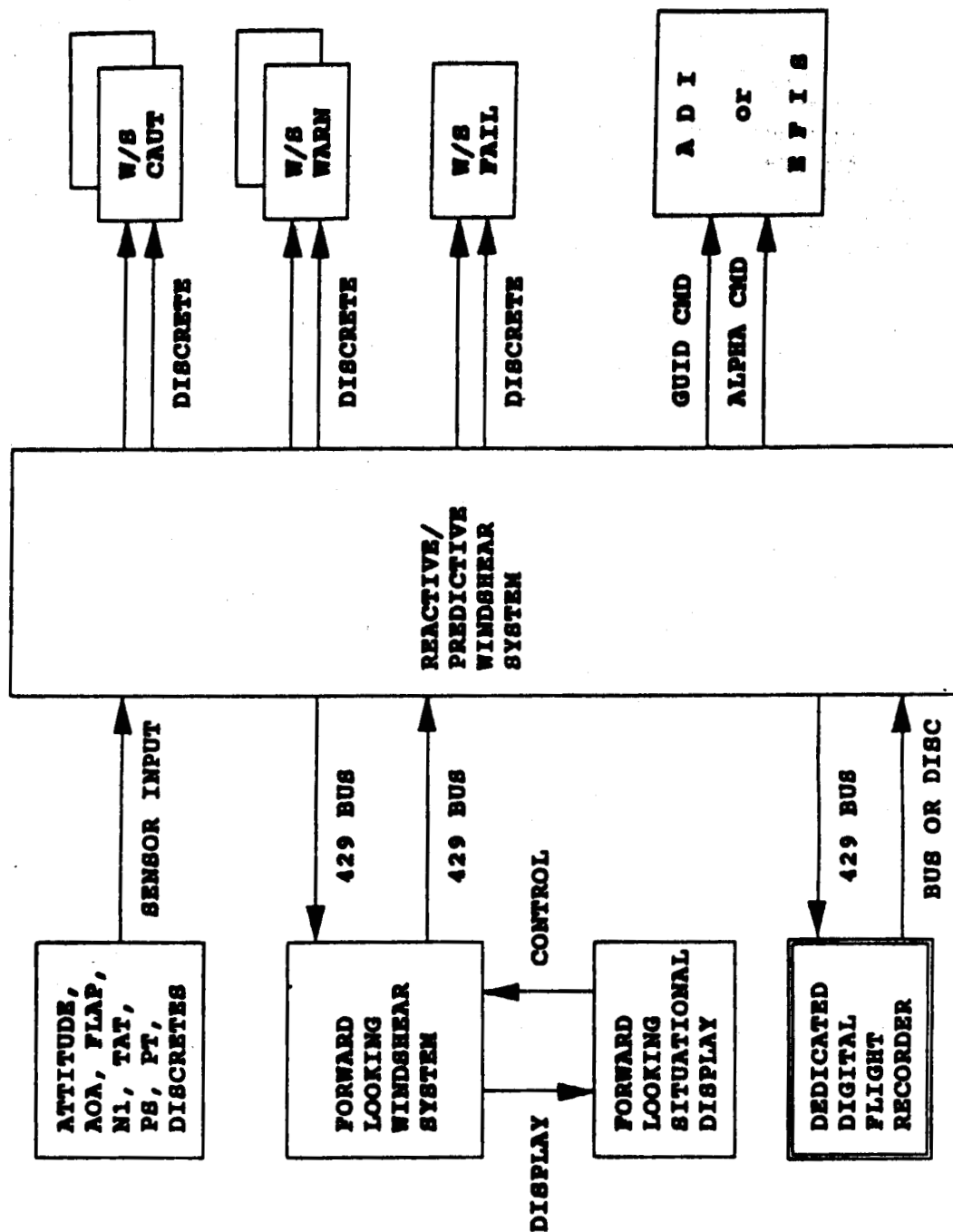
# INTERFACE STANDARDS FOR INTEGRATED FORWARD-LOOKING/PREDICTIVE/REACTIVE WINDSHEAR SYSTEMS

## DEFINITIONS:

REACTIVE SYSTEM	-	A SYSTEM WHICH UTILIZES INSITU TECHNIQUES TO MEASURE WINDSHEAR
PREDICTIVE SYSTEM	-	A SYSTEM WHICH UTILIZES METEOROLOGICAL DATA (TEMPERATURE LAPSE RATE, FREEZING POINT ALT, DEW POINT, ETC.) TO DETERMINE THE PRESENCE OF AN UNSTABLE AIR MASS
FORWARD-LOOKING SYSTEM	-	A SYSTEM WHICH UTILIZES FORWARD-LOOKING TECHNIQUES (INFRARED, DOPPLER RADAR, LIDAR) TO MEASURE WINDSHEAR
CAUTION ALERT	-	THE CAPTAIN'S AND FIRST OFFICER'S AMBER CAUTION LAMPS ACTIVATED BY THE REACTIVE SYSTEM
WARNING ALERT	-	THE CAPTAIN'S AND FIRST OFFICER'S RED WARNING LAMPS ACTIVATED BY THE REACTIVE SYSTEM
AURAL ALERT	-	THE AURAL MESSAGE ACTIVATED BY THE REACTIVE SYSTEM
SITUATIONAL DISPLAY	-	THE DISPLAY UTILIZED BY THE FORWARD-LOOKING SYSTEM TO INDICATE THE POSITION OF THE COMPUTED EVENT



# INTEGRATED FORWARD-LOOKING/PREDICTIVE/REACTIVE WINDSHEAR SYSTEM BLOCK DIAGRAM



The dedicated digital flight recorder is shown to emphasize the need for a recorder interface which will be used in the certification of any of the three (reactive, predictive, or forward-looking) windshear systems. Data that is gathered as part of the development process and flight test of the forward-looking system would be used to demonstrate the nuisance characteristics and possibly the determination of valid windshear detections.

#### 4.0 ANNUNCIATION OPTIONS

Now that we have integrated the systems in the aircraft we need to define and provide the proper annunciations to the flight crew. Current reactive annunciations (as defined in AC25-12) are indicated on Slide No. 4. If we extend this philosophy of flashing amber meaning headwind or updraft (unstable air), then a steady (steady because it's predictive) amber could also mean a detected unstable airmass. Note that this is only valid in approach and although the annunciation activation occurs once a minimum landing configuration is selected, the predictive system is gathering data throughout the entire descent profile.

Forward-looking systems are a bit harder to categorize. Since the IR detects only the cold downflow (decreasing performance), while the DOPPLER or LIDAR can detect only the outflows (increasing and decreasing performance) we can simplify and determine that if any type of forward-looking system has detected a decreasing performance shear and the aircraft is in a potentially low energy state (takeoff roll, takeoff, approach, or go-around) then the action is the same as if the reactive system had detected the shear, ie., activate the flashing red warning lamps along with the windshear aural warning annunciation.

It is recognized that other options are open. The type of information displayed on a situational display when the aircraft is outside of the low energy state, such as outside the outer marker or as a clear air turbulence indication are examples. These displays are separate and independent of the interface to the reactive system.

#### 5.0 DATA BUS PARAMETERS

Slide No. 5 defines the types of data the reactive system has access to and should be sent to the forward-looking system to simplify its interface to the aircraft. The forward-looking system would use these inputs to perform scanning stabilization, sensor cross check, and mode transition, thereby allowing the two systems to work together.

Slide No. 6 defines the typical data that is available from a forward-looking system that could be sent to the reactive system. The hazard index or intensity level would be used to activate the red warning alert.

# INTEGRATED FORWARD-LOOKING/PREDICTIVE/REACTIVE WINDSHEAR SYSTEM ANNUNCIATION OPTIONS

## LOW LEVEL WINDSHEAR DETECTION

TYPE OF DETECTION	ANNUNCIATION		CANCEL	ACTIVATION
	VISUAL	AURAL		
REACTIVE POSITIVE ENERGY	FLASHING AMBER	OPTIONAL	NO	T/R, T/O, APP, G/A
REACTIVE NEGATIVE ENERGY	FLASHING RED	WINDSHEAR (3)	NO	T/R, T/O, APP, G/A
PREDICTIVE	STEADY AMBER	OPTIONAL	NO	APPROACH*
FORWARD-LOOKING	FLASHING RED	WINDSHEAR (3)	NO	T/R, T/O, APP, G/A

\* - MINIMUM LANDING CONFIGURATION (FLAPS/GEAR) OR TBD ALT AGL AS APPLICABLE

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# INTEGRATED FORWARD-LOOKING/PREDICTIVE/REACTIVE WINDSHEAR SYSTEM DATA BUS PARAMETERS

## REACTIVE SYSTEM OUTPUTS

PARAMETER NAME	ARINC LABEL	UPDATE RATE	PRIMARY USE BY FORWARD LOOKING SYSTEM
PITCH - DEGREES	324	16 HZ	STABILIZATION FOR SCANNING FUNCTION
ROLL - DEGREES	325	16 HZ	STABILIZATION FOR SCANNING FUNCTION
TAT - DEG C	211	4 HZ	IR COMPENSATION/SENSOR CROSS CHECK
SAT - DEG C	213	4 HZ	IR COMPENSATION/SENSOR CROSS CHECK
PRESS ALT - FEET	203	16 HZ	MODE LOGIC
TAS - KNOTS	210	8 HZ	MODE LOGIC
WSC MODE/STATUS	TBD	8 HZ	MODE LOGIC/FAILURE MONITORING
WSC DISCRETES	TBD	8 HZ	MODE LOGIC

# **INTEGRATED FORWARD-LOOKING/PREDICTIVE/REACTIVE WINDSHEAR SYSTEM DATA BUS PARAMETERS**

## **FORWARD-LOOKING SYSTEM OUTPUTS**

TYPE OF SYSTEM	MEASURED DATA	COMPUTED DATA		ARINC 429 DATA TRANSFER
		NEAR TEMP - DEG C	DELTA TEMP - DEG C	
INFRARED	FAR TEMP - DEG C		LONG WIND - KNOTS	NEW ARINC 429 LABELS ASSIGNED FOR EACH PARAMETER  NON STANDARD LABELS COULD BE USED FOR ENG TELEMETRY DATA DURING SENSOR EVALUATION
			HAZARD INDEX	
			TELEMETRY/MODE	
DOPPLER RADAR	LONG WIND - M/SEC		INTENSITY LEVEL	LOW SPEED 429 WITH FORMAT SIMILAR TO CURRENT ARINC 708 WEATHER RADAR  DATA INCLUDES: PREAMBLE, AZIMUTH ANGLE, INTENSITY PER RANGE BIN
			AZIMUTH ANGLE	
			MODE/STATUS	
LIDAR	LONG WIND - M/SEC		INTENSITY LEVEL	PROPOSE SAME AS DOPPLER RADAR
			AZIMUTH ANGLE	
			MODE/STATUS	

## **Session II. Airborne—Hazard Definition**

## **Session II. Airborne-Hazard Definition**

Heavy Rain Effects on Airplane Performance  
R. E. Dunham, Jr., G. M. Bezos, and B. A. Campbell, NASA LaRC  
W. D. Mace, Jr., PRC/Kentron Inc.  
W. E. Melson, Jr., Wallops Flight Facility

## HEAVY RAIN EFFECTS ON AIRPLANE PERFORMANCE

R. E. Dunham, Jr., G. M. Bezos, and B. A. Campbell  
NASA Langley Research Center  
Hampton, VA 23665

W. D. Mace, Jr.  
PRC/Kentron Inc.  
Hampton, VA 23665

and

W. E. Melson, Jr.  
Wallops Flight Facility  
Wallops Island, VA 23337

## ABSTRACT

The objective of this activity is to determine if the aerodynamic characteristics of an airplane are altered while flying in the rain. Wind-tunnel tests conducted at the NASA Langley Research Center (LaRC) have shown losses in maximum lift, reduction in stall angle, and increases in drag when a wing is placed in a simulated rain spray. For these tests the water spray concentration used represented a very heavy rainfall. A lack of definition of the scaling laws for aerodynamic testing in a two-phase, two-component flow makes interpolation of the wind-tunnel test uncertain.

Tests of a large-scale wing are to be conducted at the LaRC. The large-scale wing is mounted on top of the Aircraft Landing Dynamics Facility (ALDF) carriage. This carriage (which is 70-foot long, 30-foot wide, and 30-foot high) is propelled with the wing model attached down a 3000-foot long test track by a water jet at speeds of up to 170 knots. A simulated rain spray system has been installed along 500 foot of the tests track and can simulate rain falls from 2 to 40 inches/hour. Operational checks are underway and the initial tests should be completed by the Fall of 1989.



# **HEAVY RAIN EFFECTS**

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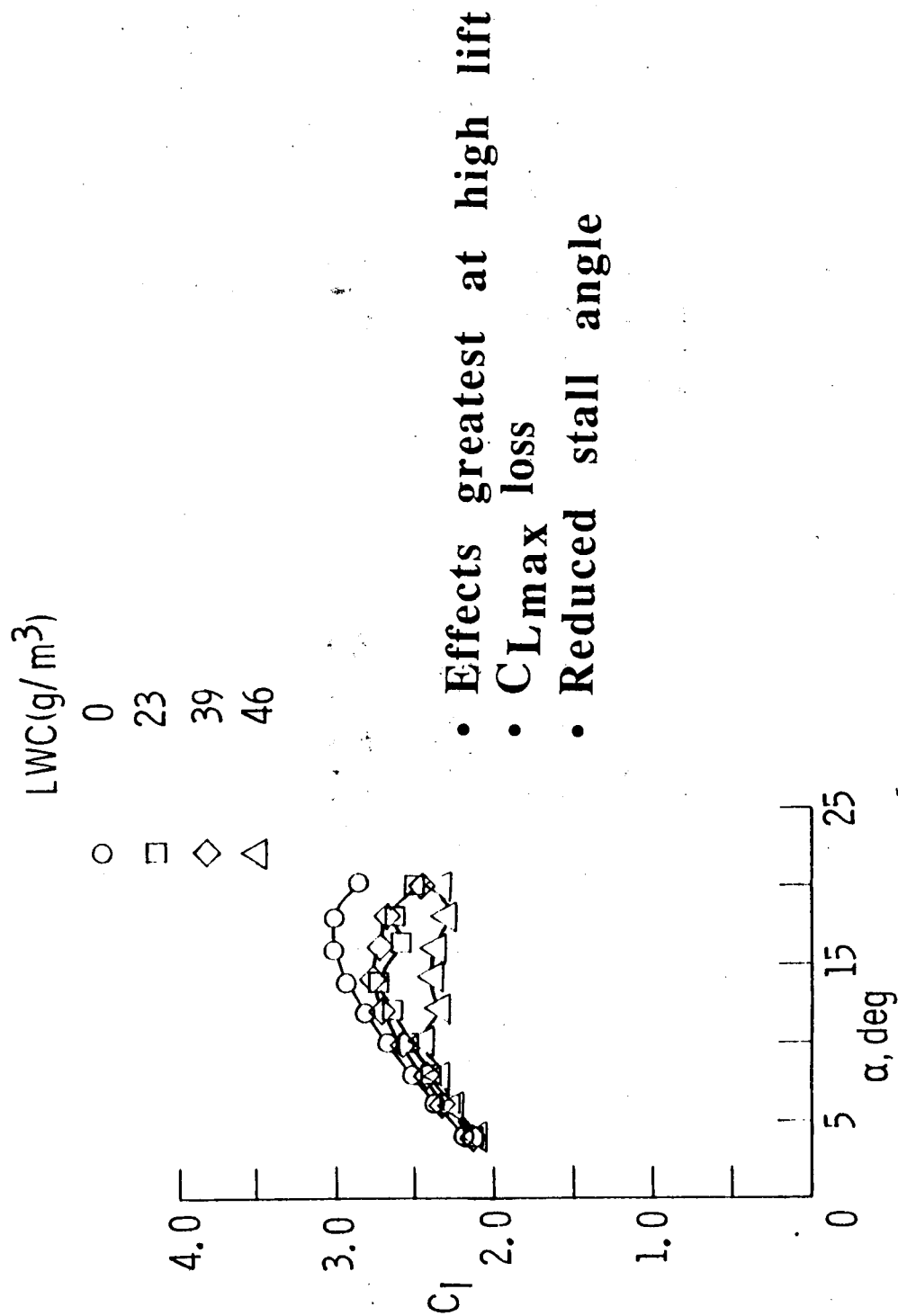
## **TECHNICAL ISSUE**

**ARE THE AERODYNAMIC CHARACTERISTICS OF AN  
AIRPLANE ALTERED WHILE FLYING IN THE RAIN?**

# **HEAVY RAIN EFFECTS**

- **Wind Tunnel Tests**
- **Large Scale Tests**
- **Results**
- **Status and Plans**

# WIND TUNNEL TESTS RESULTS



# Scaling of Test Results

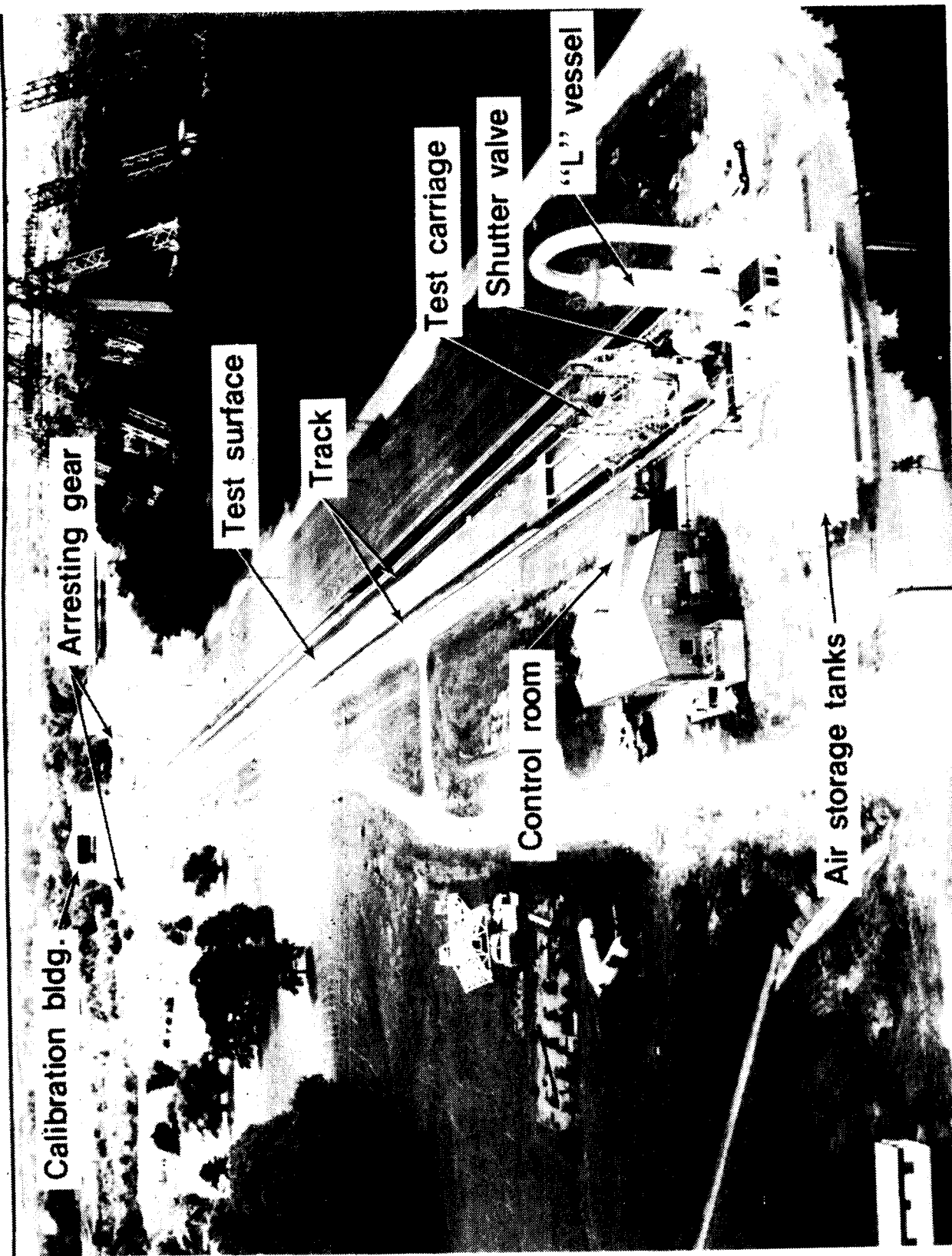
## "Dry Aerodynamics"

- $C_L = f$  (angle of attack, Reynold's Number, Mach Number)
- Scaling Laws Established

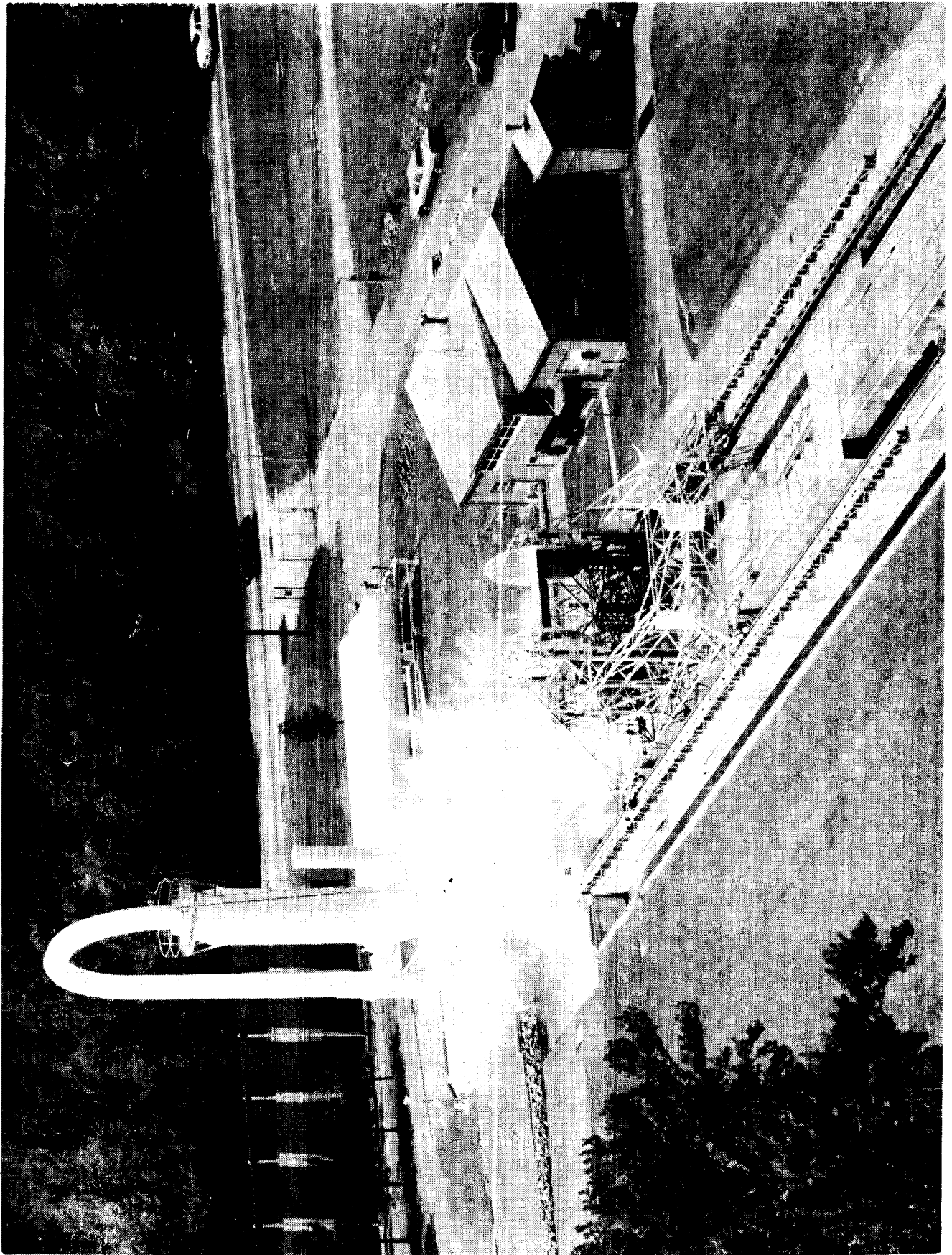
## "Wet Aerodynamics"

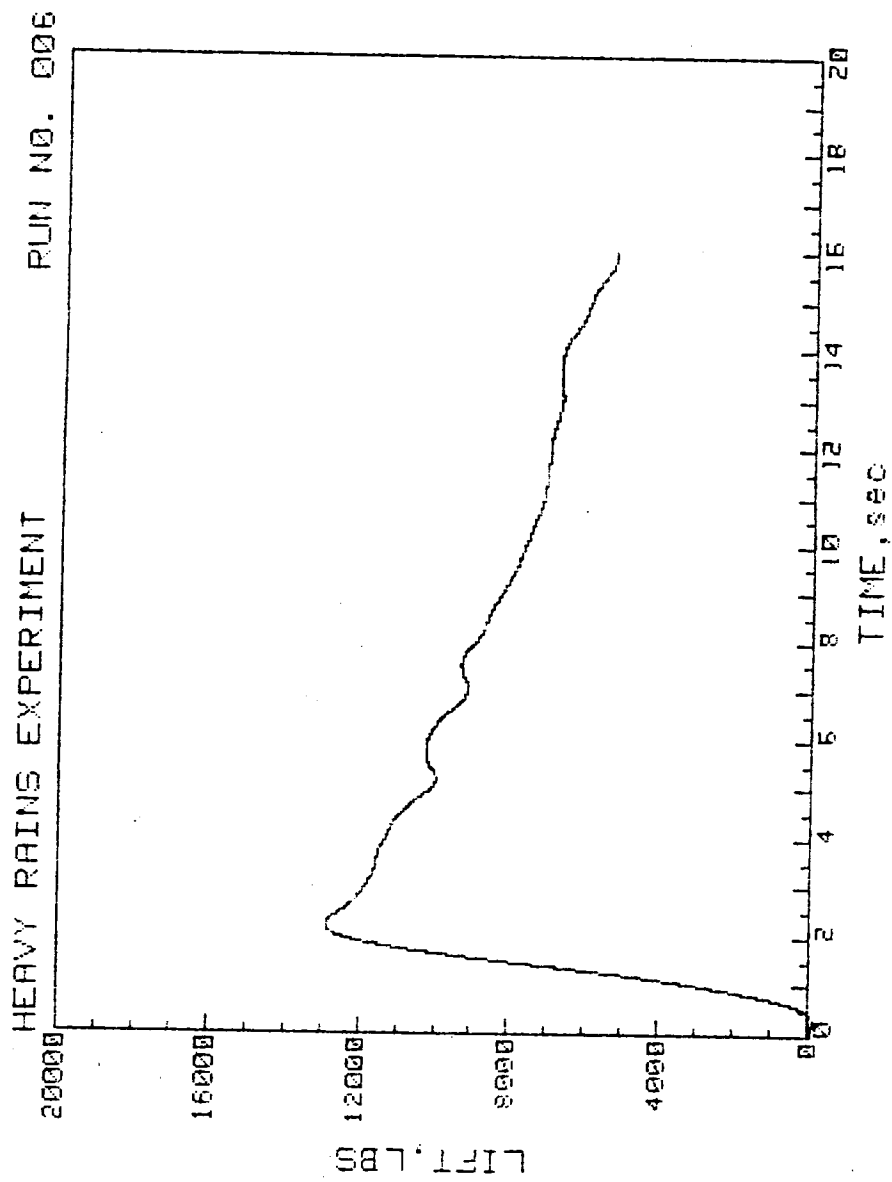
- $C_L = f$  (angle of attack, Reynold's Number, Mach Number, Weber Number, Geometric Scaling of spray drop diameter and spacing)
- No Scaling Laws Available

# AIRCRAFT LANDING DYNAMICS FACILITY



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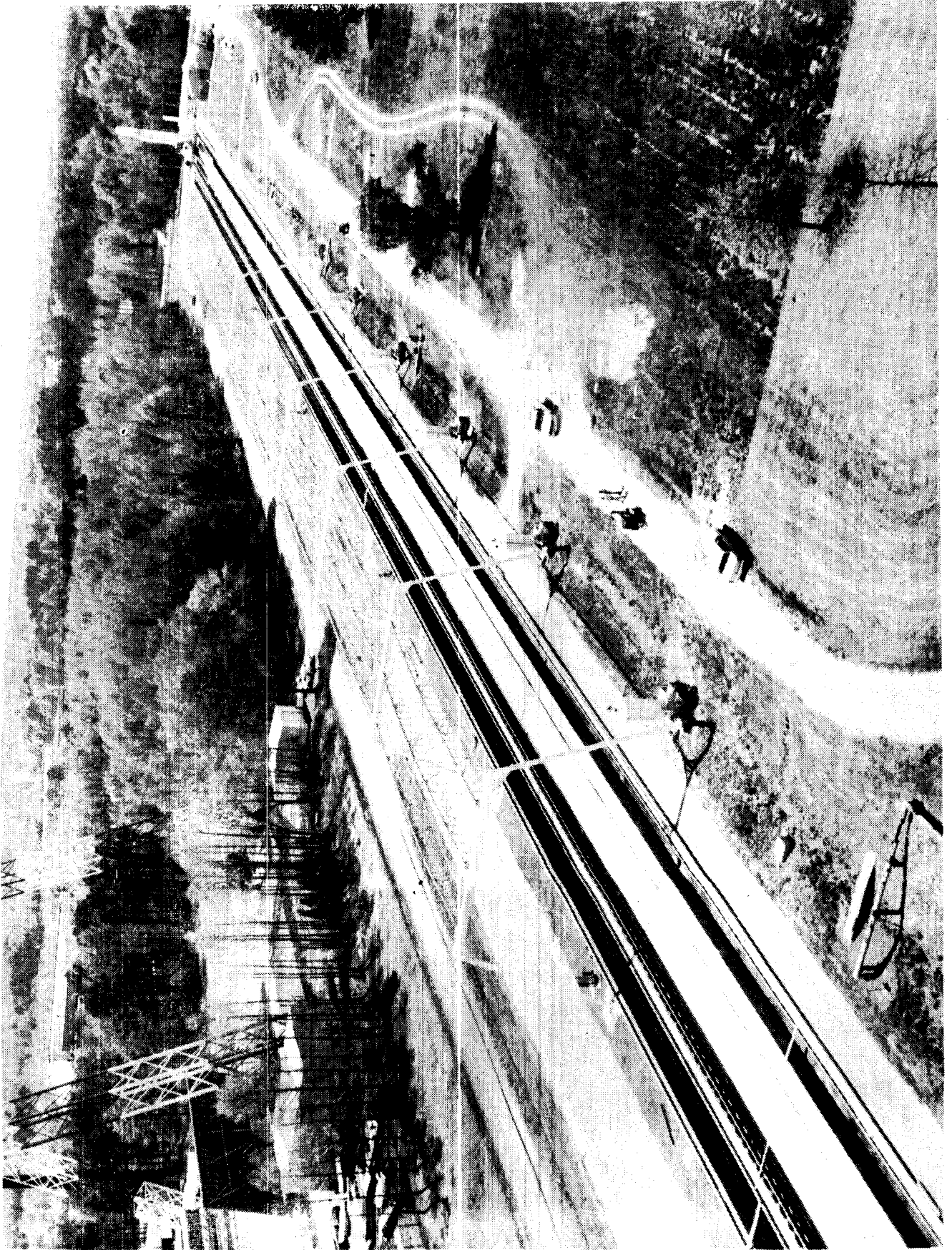


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Langley Research Center  
Hampton, Virginia 22060-0225

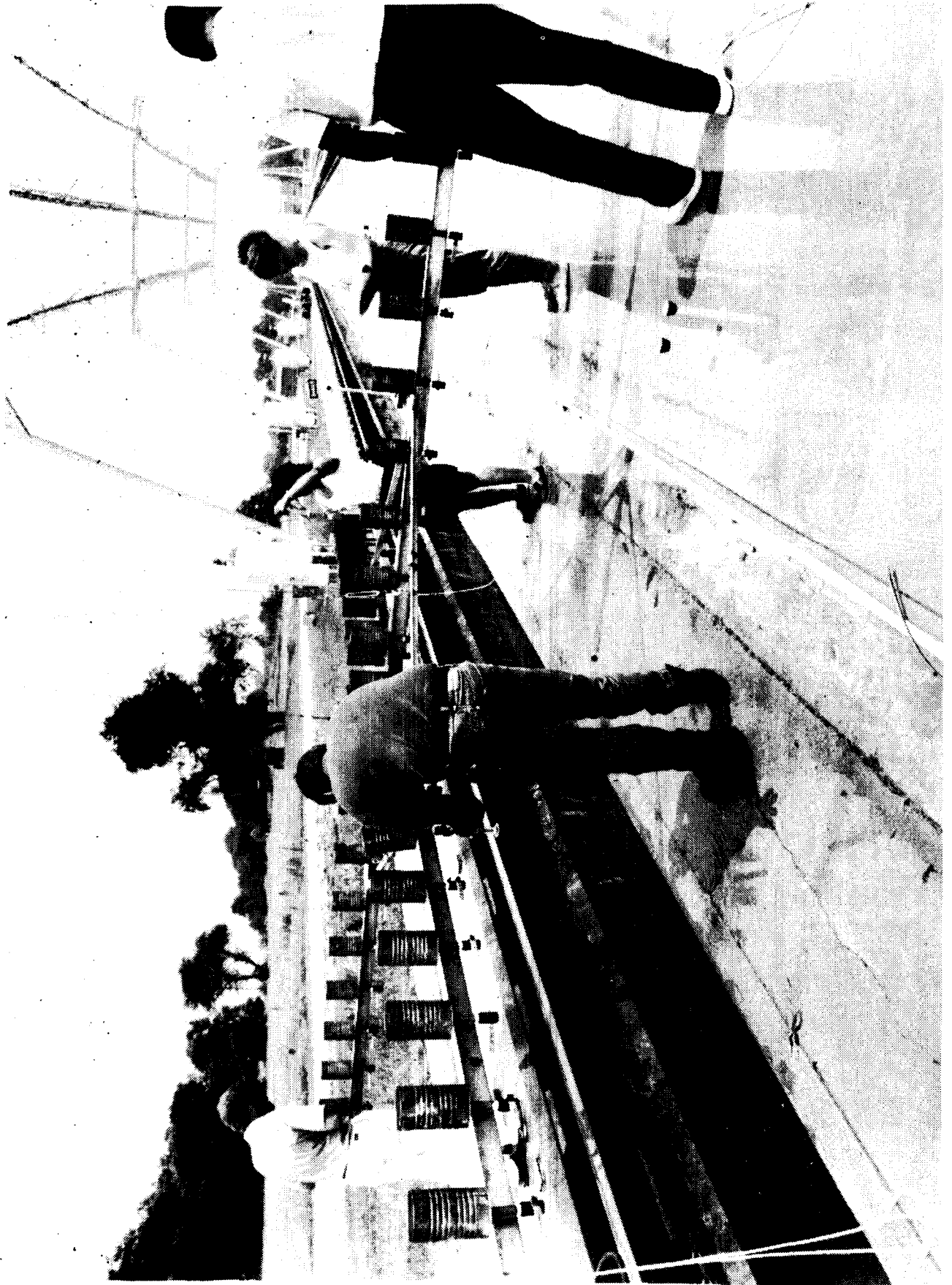
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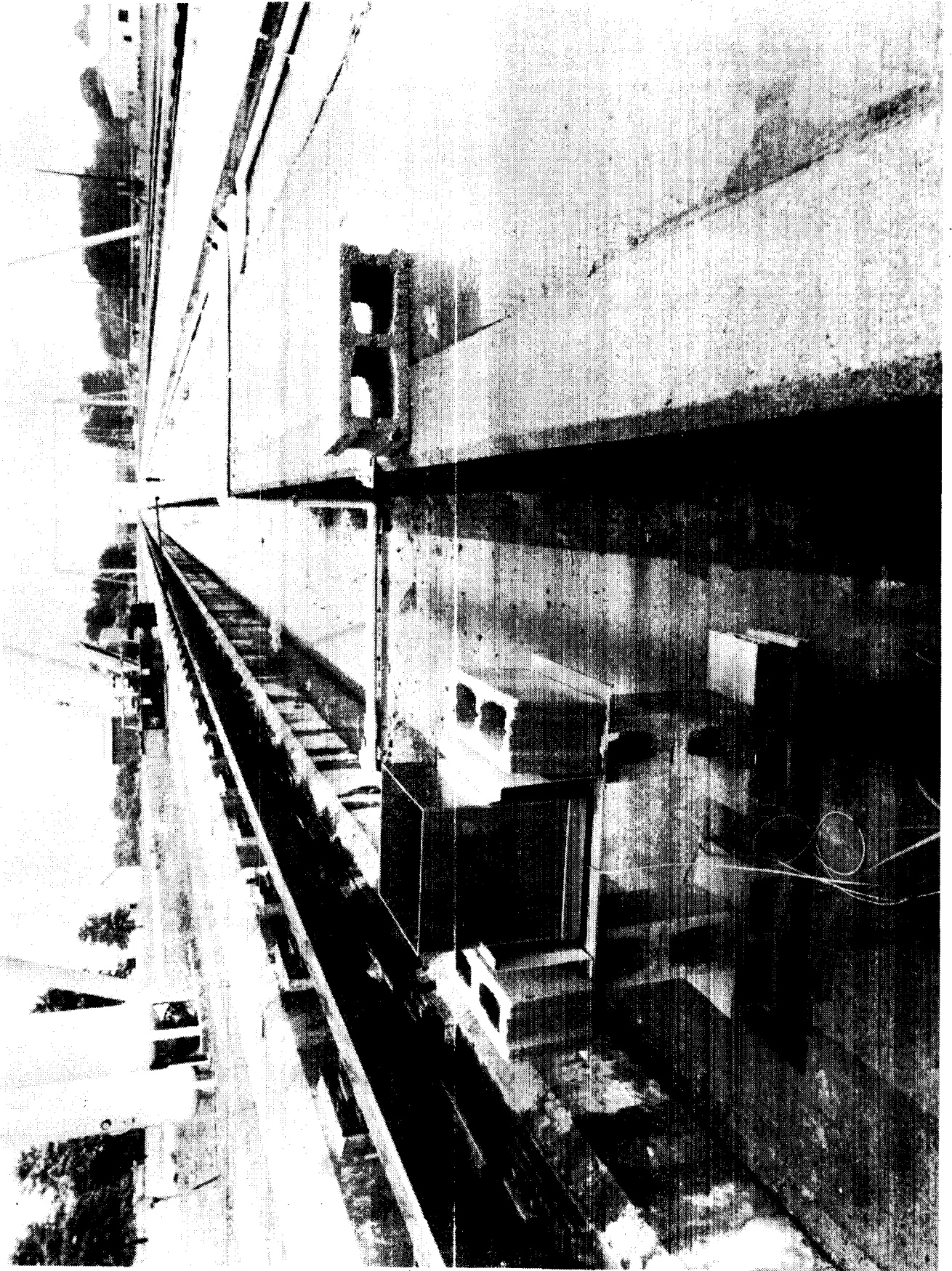


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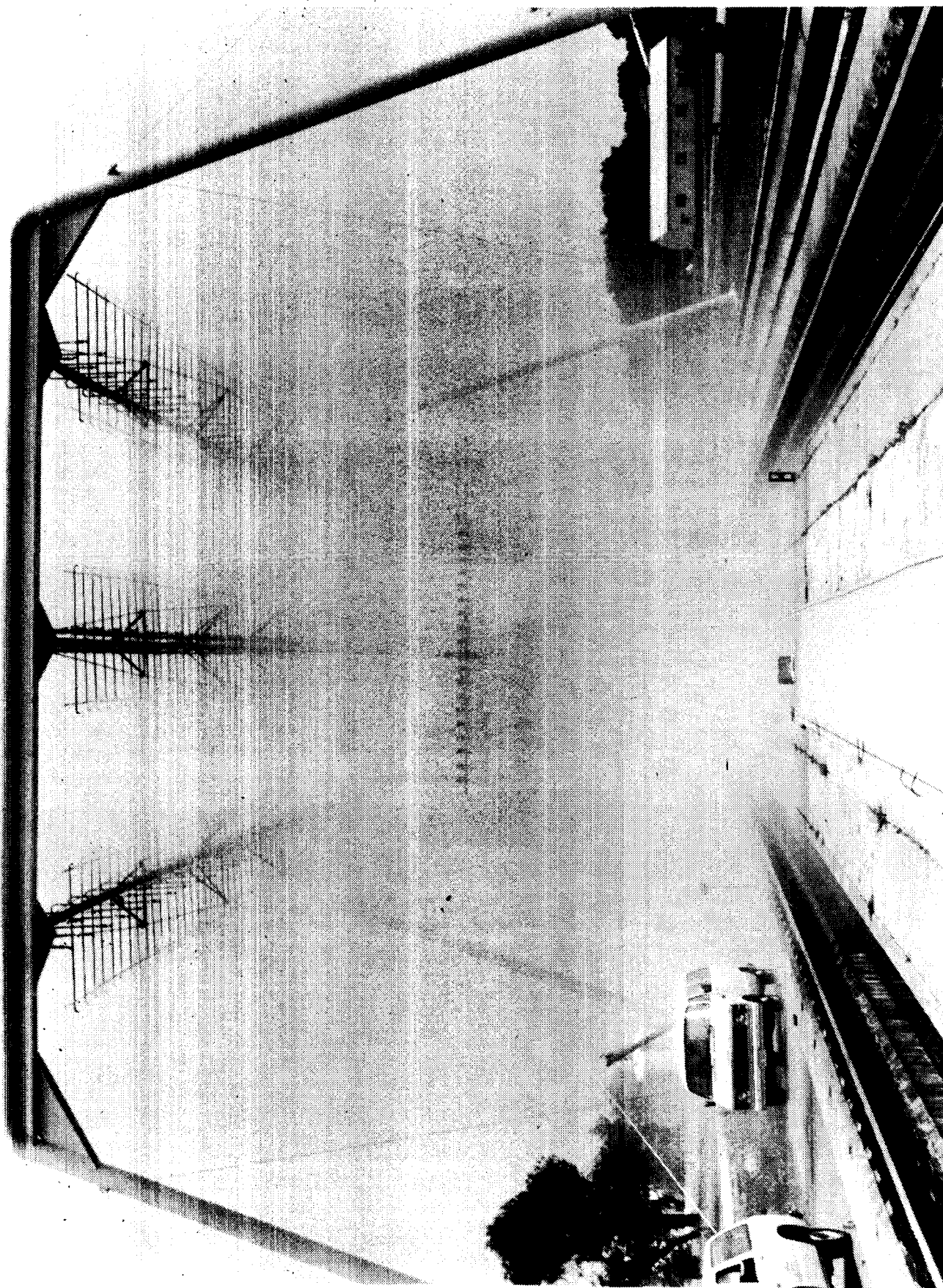
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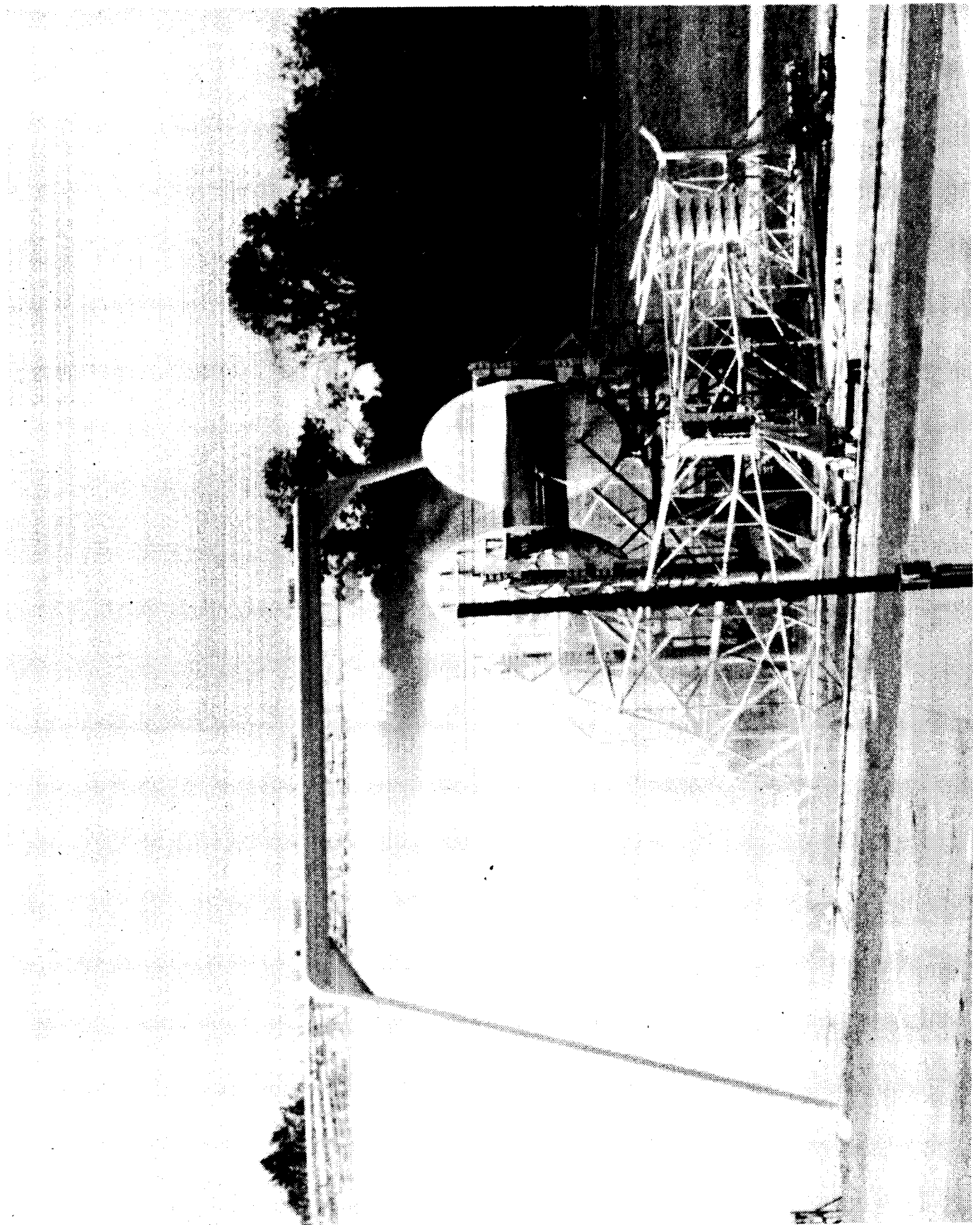
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# Large Scale Tests

- Spray system operational
- Wing/carriage Engineering checkout in progress
- Preliminary results indicate system capable of providing good aerodynamic data
- Majority of tests matrix to be completed by Fall 1989

## **Session II. Airborne—Hazard Definition**

**A Proposed Definition for a Pitch Attitude Target for the Microburst  
Escape Maneuver  
Richard S. Bray, NASA ARC**

A PROPOSED DEFINITION FOR A PITCH ATTITUDE TARGET  
FOR THE MICROBURST ESCAPE MANEUVER

p74

Richard S Bray  
NASA Ames Research Center  
Moffett Field, California

## SUMMARY

The Windshear Training Aid promulgated by the FAA defines the practical recovery maneuver following a microburst encounter as application of maximum thrust accompanied by rotation to an aircraft-specific target pitch attitude. In search of a simple method of determining this target, appropriate to a variety of aircraft types, a computer simulation was used to explore the suitability of a pitch target equal in numerical value to that of the angle of attack associated with stall warning. For the configurations and critical microburst shears simulated, this pitch target was demonstrated to be close to optimum.

## BACKGROUND

In January, 1987, the FAA released the Windshear Training Aid (reference 1), a package of documentation and visual materials defining procedures and contents of a recommended training course for pilots on the subject of microburst wind shear. The primary target of this effort was the civil air-transport community, and the material was derived and presented in the context of the operation of large jet transport aircraft. While most of the extensive educational material contained in the documents was not aircraft-specific in nature, those sections dealing with escape from microburst encounters, and especially the simulator training programs, specifically considered the B-727 aircraft.

It is recommended in Reference 1 that, upon recognition of encounter with a severe wind shear, the pilot should command full thrust and rotate the aircraft to a specified target pitch attitude. In the supporting documentation, the procedure used in defining this pitch target for the B-727 is described. The process consisted of determining the attitude that resulted in survival in the strongest shear, with a minimum exposure to a stall-warning angle-of-attack condition. This was accomplished with the use of a mathematical model of the aircraft in computations of trajectories resulting from various pitch attitudes. The selected value, 15 degrees, was not described as related to any other aircraft-specific measure. More recently, Lockheed, using a similar approach, developed the recommendation that a pitch target of 17 degrees be used in the case of the L1011 aircraft. The documents imply that this same procedure be used for developing escape procedures for each aircraft type and model. The following paragraphs propose and discuss examination of a simpler pitch target definition that might be applied to any aircraft configuration.

## THE PREMISE

It is noted that the pitch targets chosen for the B-727 and the L1011 crudely approximate the numerical values of the angles-of-attack associated with the activation of their stick-shaker stall warning systems. It is also noted that if it can be assumed that extended areas of strong downdraft cannot exist near the ground, even in a microburst, an aircraft cannot descend rapidly into the ground before experiencing stall warning if its pitch attitude is at or above the numerical value of stall-warning angle of attack. (Flight path angle = pitch angle minus angle



of attack). This paper reports an examination of the premise that a pitch target, effective for a range of aircraft characteristics, is represented by the numerical value of the stall-warning angle of attack.

## PROCEDURE

The dynamic performance characteristics of three generic aircraft were defined for take-off and approach configurations in terms of wing loading,  $W/S$ , thrust-to-mass,  $T/m$ , and lift and drag. After establishing initial conditions, and defining pitch attitude and thrust for the recovery maneuver, the models were "flown" through a modelled microburst wind field using various pitch attitude targets in a procedure similar to that used in support of the Windshear Training Aid. When stall-warning angle of attack was encountered, pitch was reduced to avoid significant increase of angle of attack beyond that value. Details of the method of trajectory computation are included in Reference 2.

For each configuration, a microburst intensity was chosen that resulted in a marginal recovery using the "stall-warning angle of attack" pitch target. In the same microburst, trajectories were computed for lesser and greater recovery pitch attitudes, and the relative success, in terms of ground clearance and time near stall, were noted.

## AIRCRAFT CONFIGURATIONS

Chosen for study were generic configurations representative of three categories of aircraft; a large, high-wing-loading jet transport incorporating high-lift leading edge slats; a jet-powered configuration of lower wing loading without leading-edge devices, and a turboprop-powered configuration, also without leading-edge devices. These latter two might be considered representative of some business jets and turboprop commuter aircraft respectively. The three aircraft were assumed to be twin-engined configurations, and they were not considered to be operating at full maximum gross weight; thus, they possessed large performance margins to help them recover from shear encounters. No special effort was made to exactly match the performance margins of these models because (1) they represented categories of aircraft that experience quite different operational situations, and (2) it was not the primary intent of this work to study their relative performance in wind shear. The three aircraft will be referred to as heavy jet (HJ), light jet (LJ), and turboprop (TP). The aircraft are described in Table 1, and the maximum thrust characteristics, which vary with speed, are defined in Figure 1.

## MICROBURST MODEL

The wind fields were defined by the computational microburst model described in Reference 2. The model describes an axially symmetric downdraft column that is converted to a radially divergent outflow near the ground plane. Below a specified altitude at which divergence begins, vertical velocity reduces exponentially to zero at ground level. Considering volumetric continuity, the resultant peak horizontal divergence velocities (near the circumference of the downdraft column) increase linearly with altitude increment below the specified altitude; thus, the maximum divergence of the winds, and the maximum shear gradient, occurs near the ground. No specific vortex flow is defined, and no smaller scale turbulence is included. The amplitude of the divergence can be increased by either increasing the diameter of the microburst (holding gradient constant), or increasing the downdraft velocity (increasing gradient). For this work, the aircraft experiences winds as if it had flown directly through the center of the microburst. Basic characteristics of the microburst winds encountered by the models in this exercise are listed in Table 2.

## INITIAL CONDITIONS

The initial conditions for the start of the trajectory computations were somewhat arbitrarily chosen, as was the relative position of the modelled microburst. For take-off, the aircraft was assumed to be at 50 feet established in normal climb at a speed of  $V_2+10$  knots and just entering the headwind to tailwind shear. On approach, the aircraft was in a normal descent at 400 feet, about 10% above normal reference speed, and at reduced power, as if the aircraft had been experiencing an increasing head wind. The shear was encountered within the first two seconds. In all cases, the timing of the initiation of the recovery maneuver reflected an assumed delay in recognition of the shear, and in most cases 10 to 15 knots had been lost before action was initiated. In the approach cases, the rate of increase of thrust from its initial value to full thrust was intended to be representative of the powerplant type.

## RESULTS AND DISCUSSION

The results of a typical trajectory computations are shown for a take-off shear encounter with the HJ model in Figure 2, and for a discontinued approach with the same model in Figure 3, in which the important variables are plotted versus horizontal distance. Note that the data points represent one-second intervals.

At the initiation of the take-off calculations (Figure 2), the aircraft is assumed to be entering the microburst shear at its trimmed climb attitude of 22 degrees. After a four-second delay, in which a loss of 15 knots of airspeed occurs, pitch attitude is reduced to the pitch target of 18 degrees. In the large shear gradient, speed continues to decay, and climb rate reduces to zero at an altitude of 335 ft. At this point, the aircraft is flying in a downdraft of 23 ft/sec. With continuing reduction in airspeed, angle of attack increases until stall warning is indicated at a value of 18 degrees. In response, pitch attitude is reduced to prevent angle of attack from increasing. After 4 seconds, the shear and downdraft end, and a rapid increase in airspeed begins. Over the next 6 seconds, recovery is made at a very low altitude at high angle of attack. As indicated earlier, the microburst severity was chosen to produce a marginal recovery with this pitch attitude target.

Similar events are seen in the approach case illustrated in Figure 3. The recognition delay, together with delay in thrust response, result in only a temporary delay in further descent, and recovery again occurs as the shear ends after the aircraft has suffered a period of about six seconds at stall-warning angle of attack.

### Take-off trajectories:

The take-off trajectories for the three configurations, at various pitch attitudes, are shown in figures 4 through 6. The behavior of the HJ configuration is shown in figure 4. For this case, the breadth of the microburst shear was set at 4200 feet, and the higher altitude downdraft velocity was set at 60 feet/second. As was seen in Figure 2, for the pitch target of 18 degrees, the total horizontal shear experienced was 145 ft/sec (86 knots), and the maximum downdraft encountered was 23 ft/sec. The other trajectories reflect the effects of the same microburst model configuration. It is seen that as the pitch target is increased to 21 degrees, nearly the same recovery altitude results. A slightly higher peak altitude is reached, but the time at limit angle of attack, the pitch down and peak descent rate are greater. Data not included in the figure indicate that further increases in pitch target produce even less favorable results. As illustrated in the figure, reducing the pitch target to 15 degrees

produces the favorable effects of lower airspeed loss and less time at limit angle of attack, but the recovery altitude is lower. Further reduction of target attitude results in ground contact.

The results for the LJ configuration are shown in figure 5. In this case, stall-warning occurs at 12 degrees, and the operational pitch attitudes are generally lower than in the previous model. Increasing the pitch target to 15 degrees results in an increase of 15 ft in recovery altitude, but at the expense of a considerably greater time at limit angle of attack, and a larger pitch-down to avoid stall. A pitch target of 9 degrees results in a recovery very close to the ground.

The performances of the TP configuration are shown in figure 6. The stall warning is assumed to occur at 11 degrees. The microburst intensity is approximately the same as for the previous configurations. Speeds and peak altitudes reflect the lower operational speed of this lighter wing-loading aircraft. Again, varying the pitch target above or below 11 degrees does not result in a net improvement in recovery performance.

#### Discontinued approach trajectories:

The discontinued approach trajectories for the three configurations, at various pitch attitudes, are shown in figures 7 through 9. The behavior of the HJ configuration is shown in figure 7. For this case, the breadth of the microburst shear was set at 4400 feet, and the higher altitude downdraft velocity was again set at 60 ft/sec. As was seen in Figure 3, for the pitch target of 18 degrees, the total horizontal shear experienced was 135 ft/sec (80 knots), and the maximum downdraft encountered was 22 ft/sec. The other trajectories reflect the effects of the same microburst model configuration. An increase of the pitch target from 18 to 22 degrees resulted in a failure to recover, while a decrease to 14 degrees produced a recovery altitude only slightly lower than that seen at 18 degrees while only approaching limit angle of attack.

The performances of the LJ configuration, in the same winds, are shown in Figure 8. The effects of varying target pitch attitude are seen to be very much as those seen with the previous configuration.

Performances for the TP configuration are shown in Figure 9. In this case, the stall-warning angle of attack is assumed to be 10 degrees. It is seen that reducing the pitch target to 8 degrees results in about the same recovery altitude as produced by an attitude of 10 degrees, and again with slightly more favorable angle of attack and speed histories. On the other hand, increasing the attitude target to 13 degrees results in more adverse performance in all respects.

The less adverse sensitivity to reduced pitch attitudes in the approach case is a result of the opportunity for the aircraft to exchange altitude for airspeed. It apparently does this more efficiently at slightly reduced attitudes. As the encounter altitude is lowered, it is expected that the results would more resemble those of the take-off case, which exhibited reduced adverse sensitivity to increased pitch attitudes.

#### CONCLUDING REMARKS

In search of a simple method of determining a wind-shear recovery pitch-attitude target, appropriate to a variety of aircraft types, a computer simulation was used to explore the suitability of a pitch target equal in numerical value to that of the angle of attack associated

with stall warning. In the case of encounter shortly after lift-off, recovery success was not adversely sensitive to small increases in target attitude above that proposed, but reductions in pitch target produced less than successful results. In the approach encounters, it was seen that the reverse trend prevailed. For the three aircraft configurations and the critical microburst shears simulated, the proposed pitch target was demonstrated to be close to optimum for both take-off and low-approach encounters.

## REFERENCES

1. Windshear Training Aid, Federal Aviation Administration, Washington, D. C., 1987
2. Bray, Richard S.: Aircraft Performance and Control in Downburst Wind Shear, Paper No. 861698, SAE Aerospace Technology Conference, Long Beach, California, 1986.

Table 1: Aircraft characteristics

Definitions:

A	Angle-of-attack, deg
CL	Lift coefficient
CD	Drag coefficient
L/D	Lift/drag ratio
VREF	1.3*stall speed, knots
V2	Minimum speed, second-segment climb, knots
W/S	Wing loading, lb/ft <sup>2</sup>

Characteristics:

HJ:	$CL = CL_0 + 0.095*A - 0.000025*A^3$
	$CD = CL/L/D$
	$L/D = L/D_0 + 0.9*A - 0.055*A^2 + 0.0007*A^3$
LJ:	$L/D = L/D_0 + 0.9*A - 0.07*A^2 + 0.0005*A^3P$
TP:	$CL = CL_0 + 0.10*A - 0.000025*A^3$
	$CD = CD_0 + 0.054*(CL - DELCL)^2 + FCLT*(T/m)$

		<u>Take-off</u>	<u>Approach</u>
HJ:	CL <sub>0</sub>	0.25	0.50
	L/D <sub>0</sub>	6.0	3.0
	W/S	110	90
	V2	152	
	VREF		136
	Stall warning A = 18 deg		
LJ:	CL <sub>0</sub>	0.25	0.50
	L/D <sub>0</sub>	6.0	3.0
	W/S	79	65
	V2	152	
	VREF		136
	Stall warning A = 12 deg		
TP:	CL <sub>0</sub>	0.3	0.7
	CD <sub>0</sub>	0.05	0.14
	W/S	40	40
	V2	110	
	VREF		110
	Stall warning A	11	10
	DELCL	0.3	0.5
	FCLT	0.02	0.03

Table 2: Microburst characteristics (based on model of reference 2)

	Diameter, ft	Downdraft, ft/sec (above 1500')	Max. divergence, knots
HJ and LJ:			
Take-off	4200	60	86
Approach	4400	60	80
TP:			
Take-off	4000	62.5	87
Approach	4000	60	74

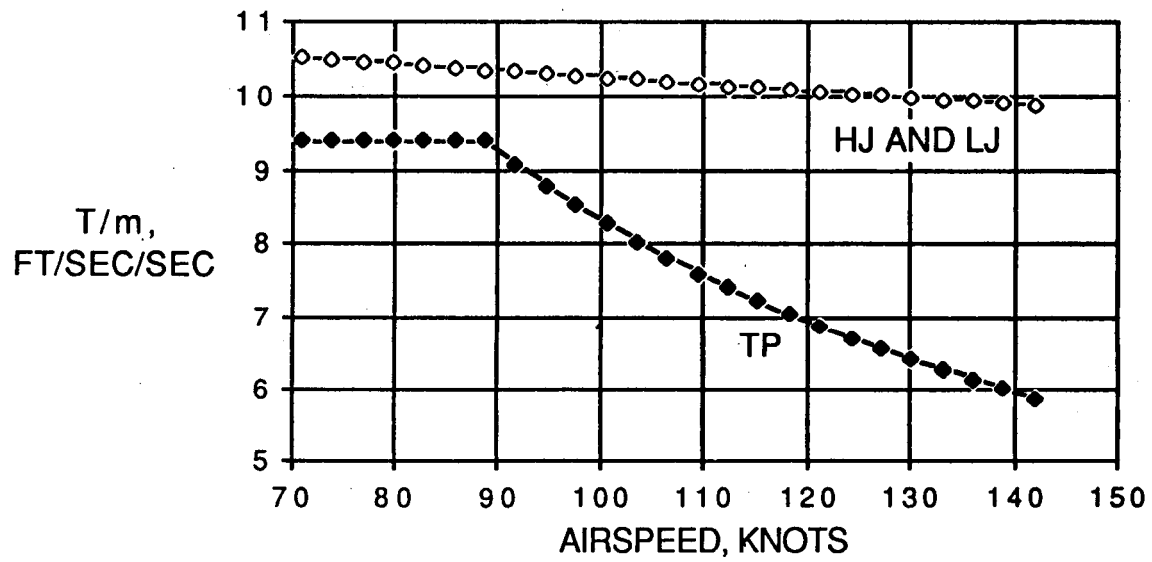
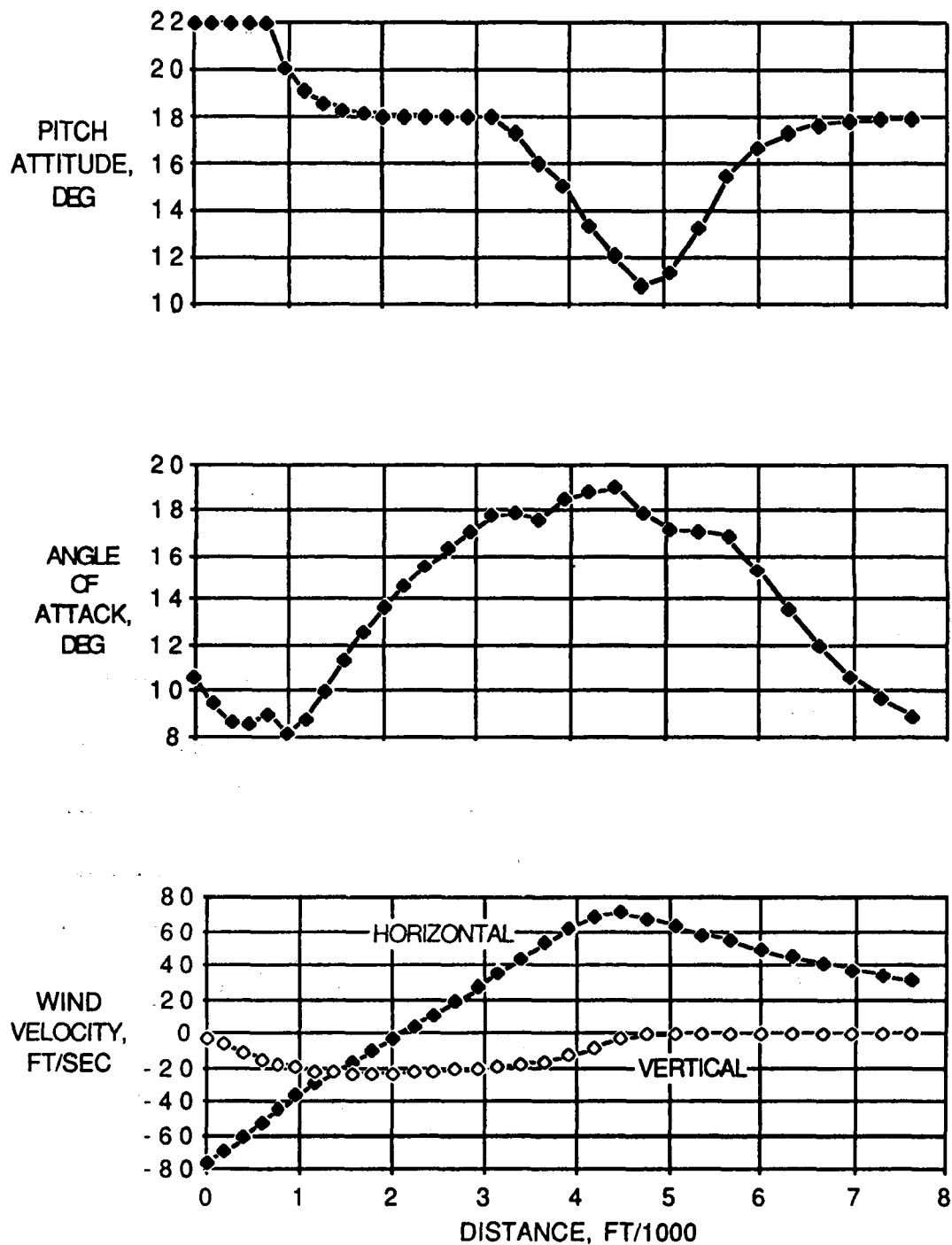
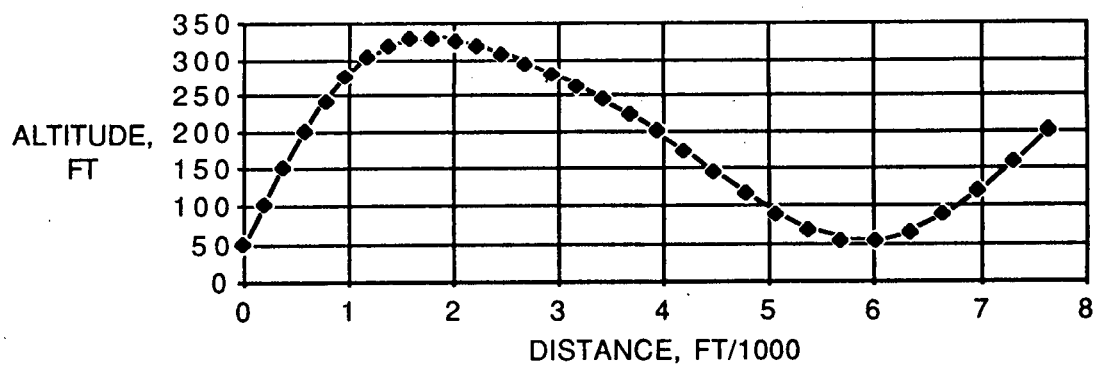
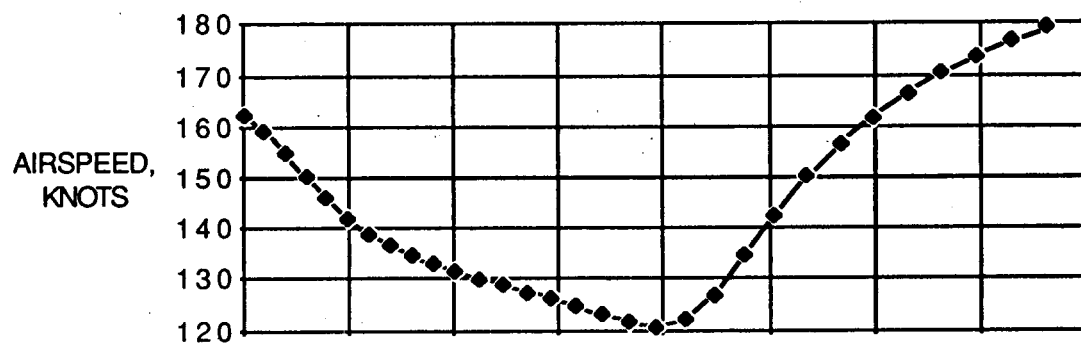
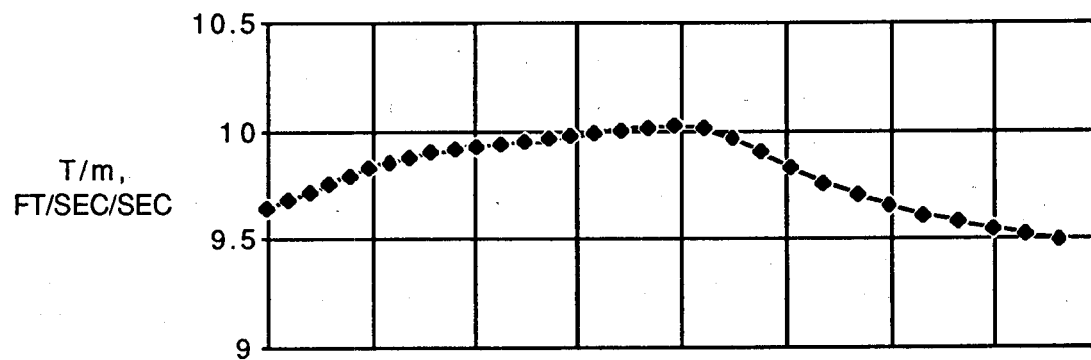


Figure 1. Variation with airspeed of acceleration due to thrust.



(a)

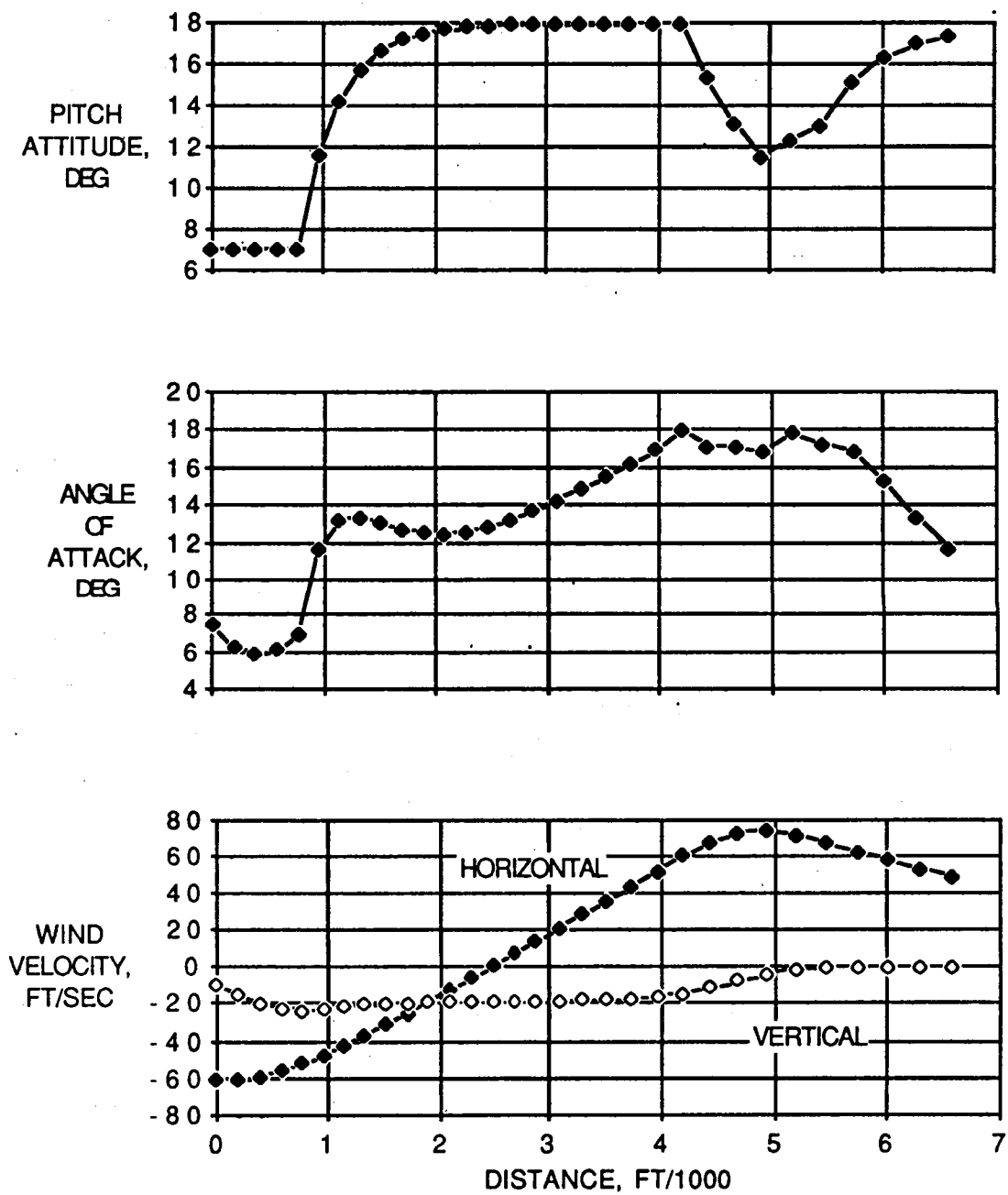
Figure 2. Performance of the HJ configuration in a take-off microburst encounter using a pitch target of 18 degrees.



(b)

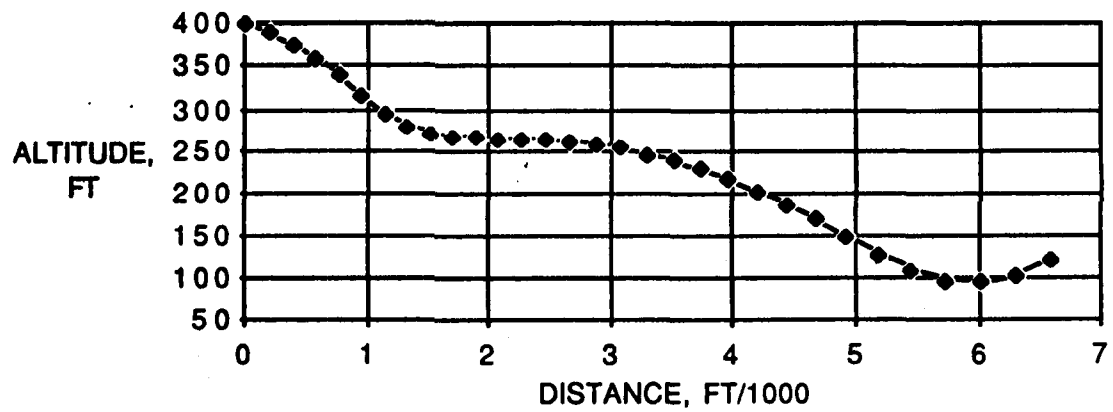
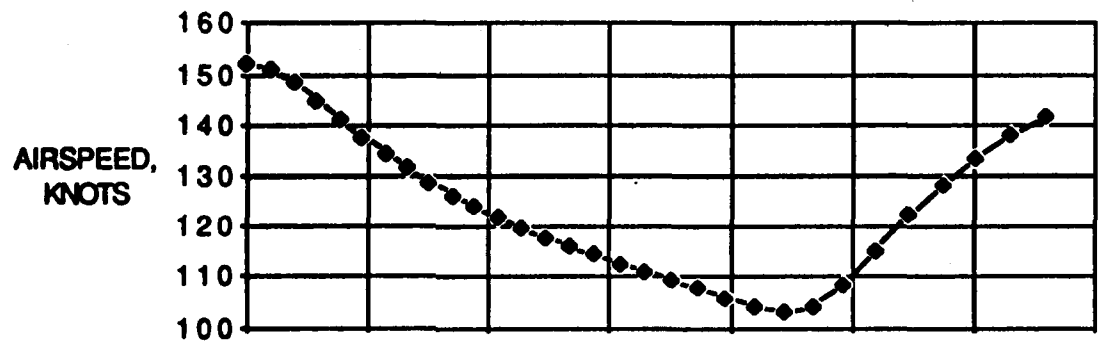
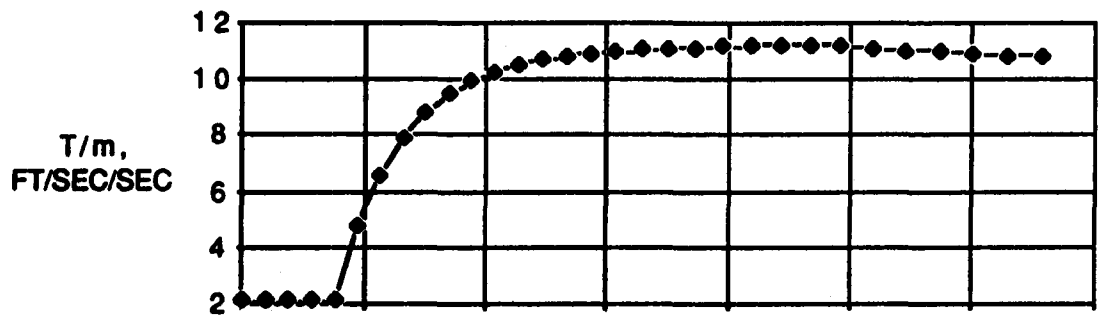
Figure 2. -continued.





(a)

Figure 3. Performance of the HJ configuration in a landing approach microburst encounter using a pitch attitude target of 18 degrees.



(b)

Figure 3. -continued.

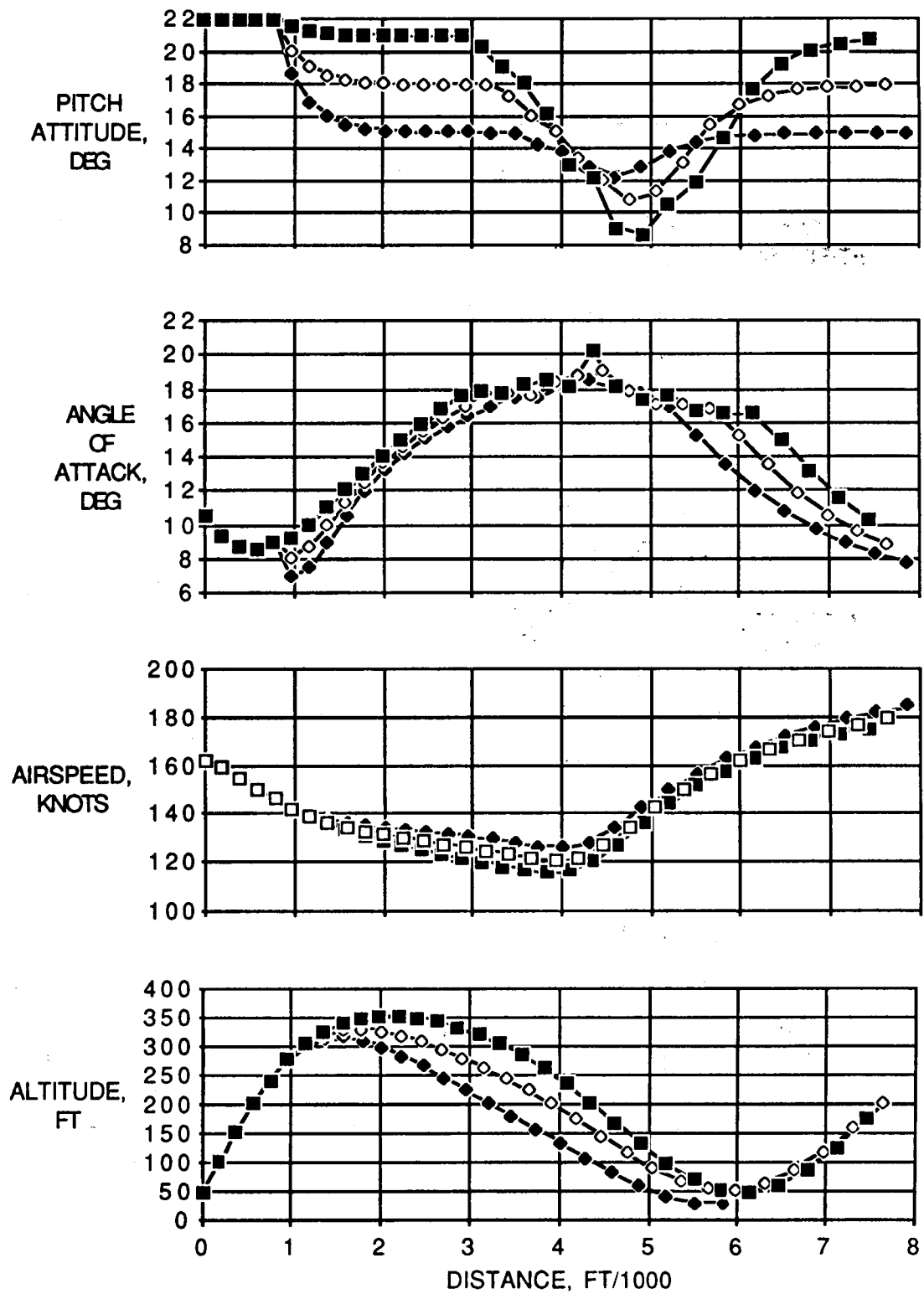


Figure 4. Performance of the HJ configuration in take-off microburst encounters.

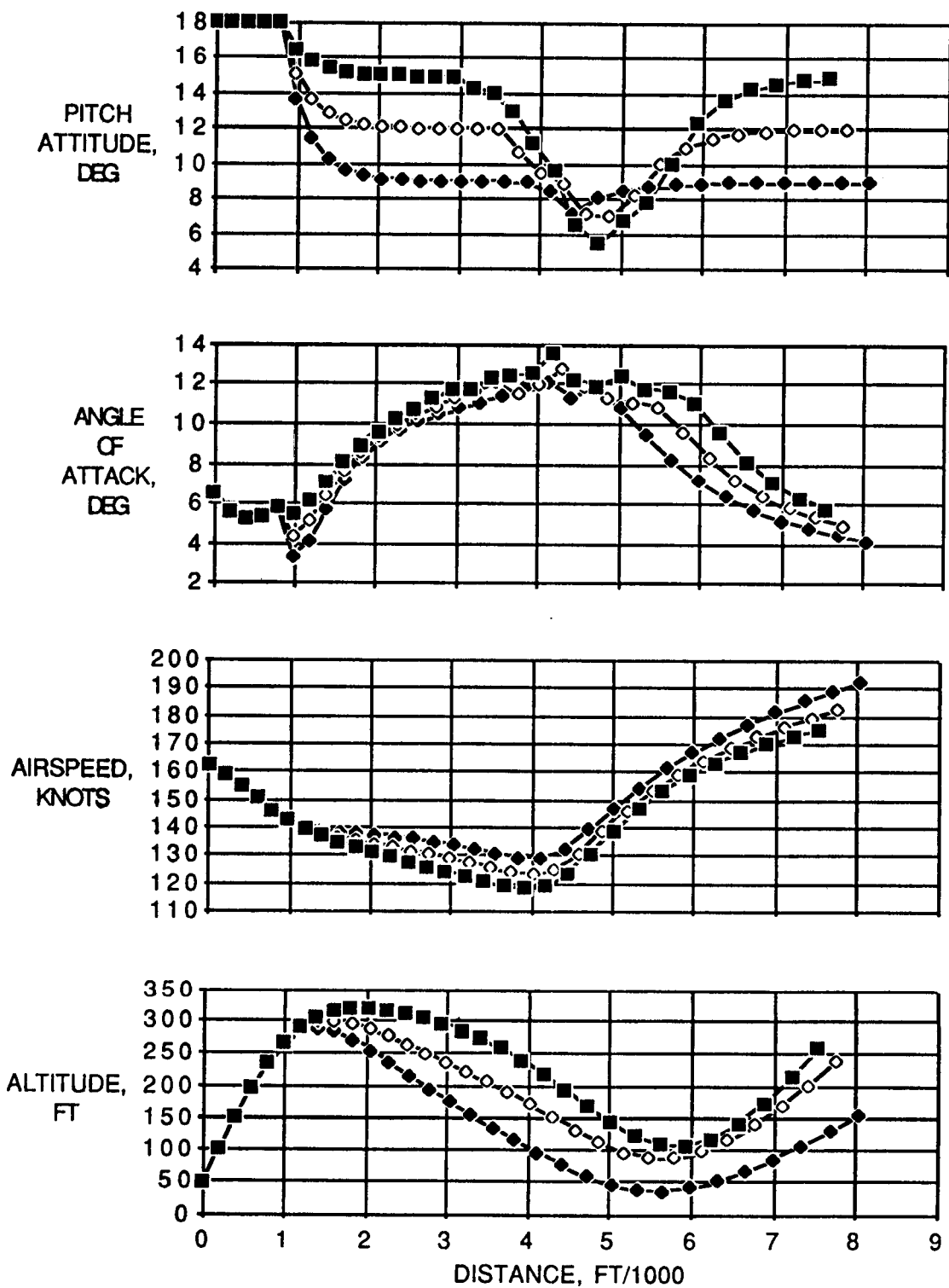


Figure 5. Performance of the LJ configuration in take-off microburst encounters.

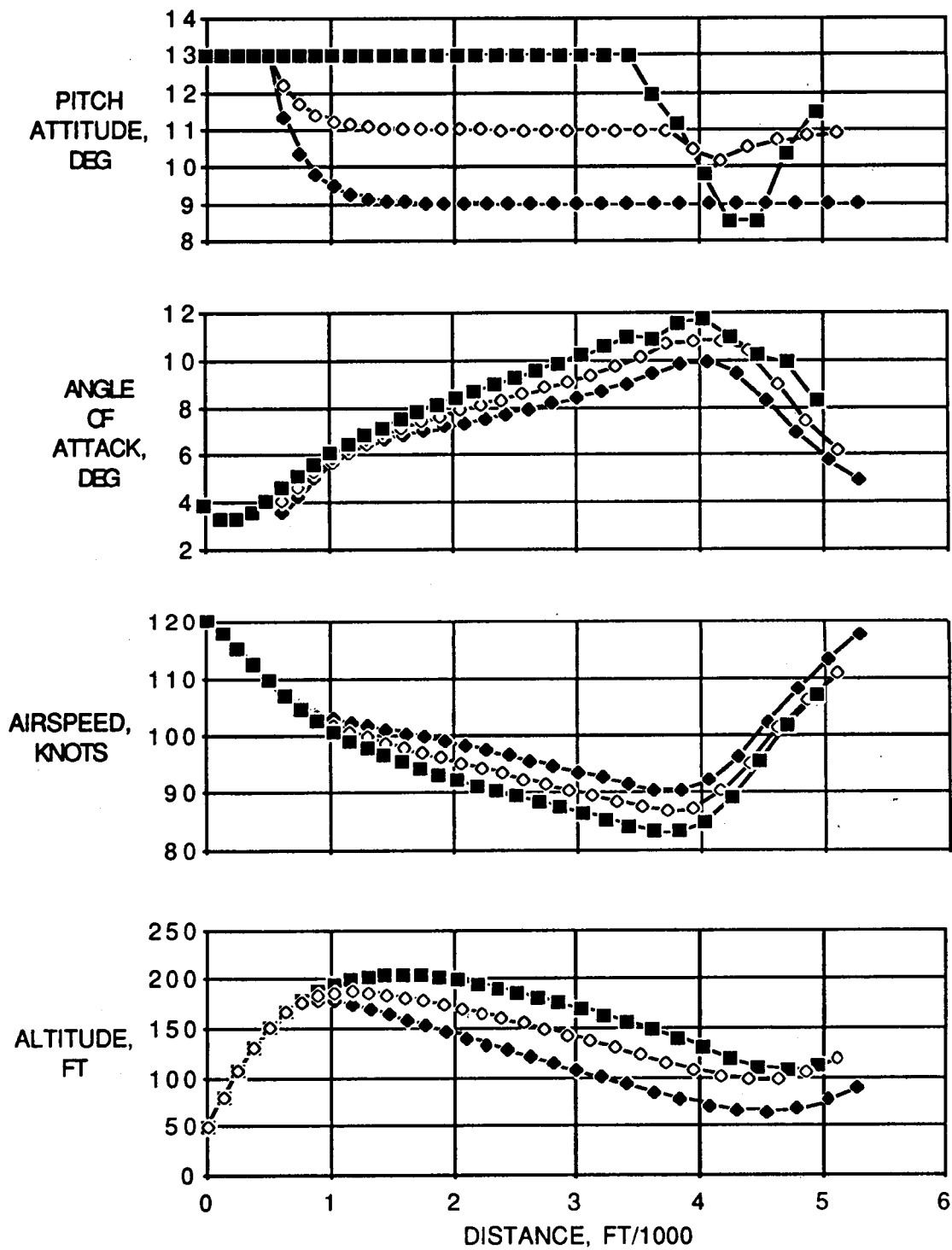


Figure 6. Performance of the TP configuration in take-off microburst encounters.

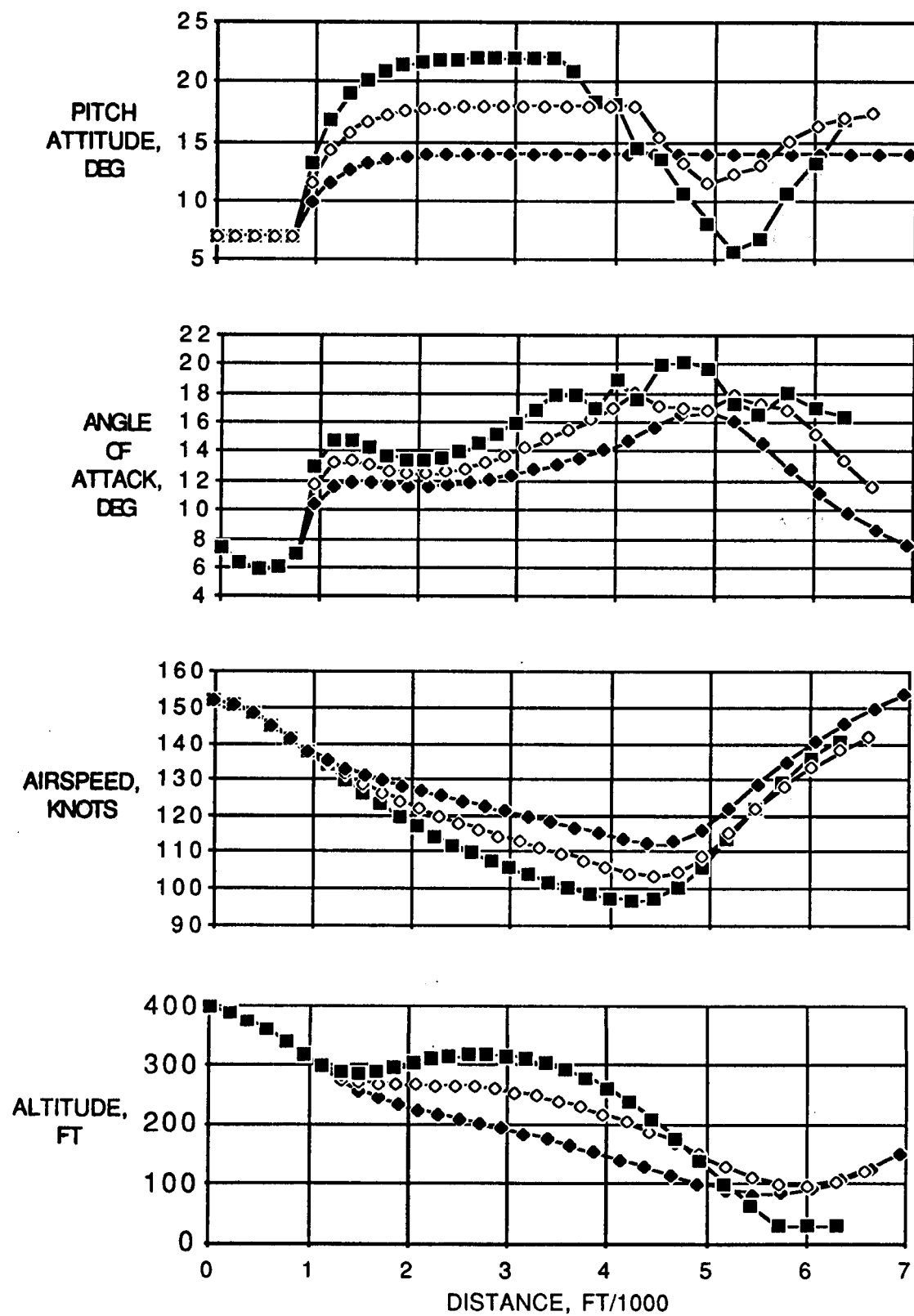


Figure 7. Performance of the HJ configuration in landing approach microburst encounters.

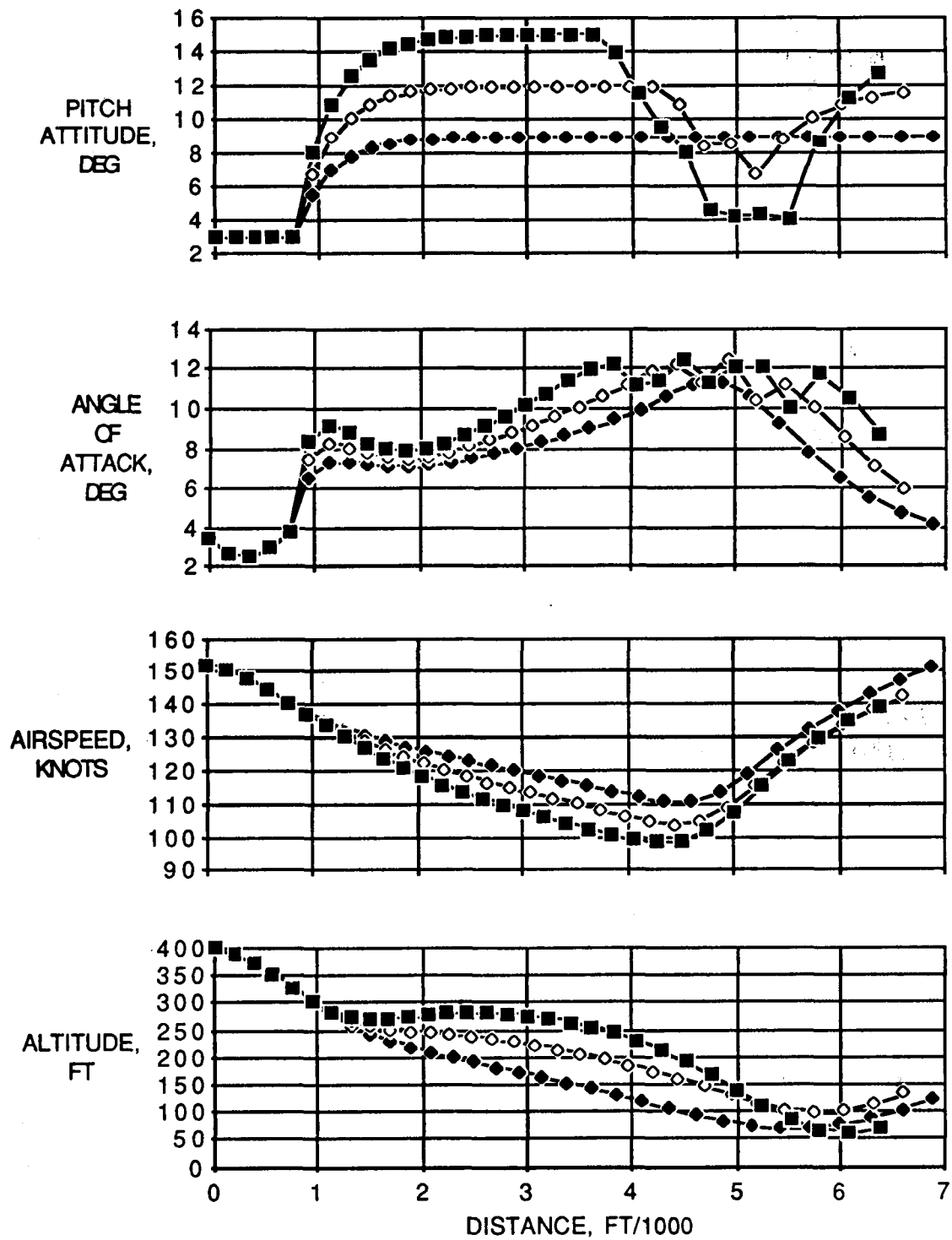


Figure 8. Performance of the LJ configuration in landing approach microburst encounters.

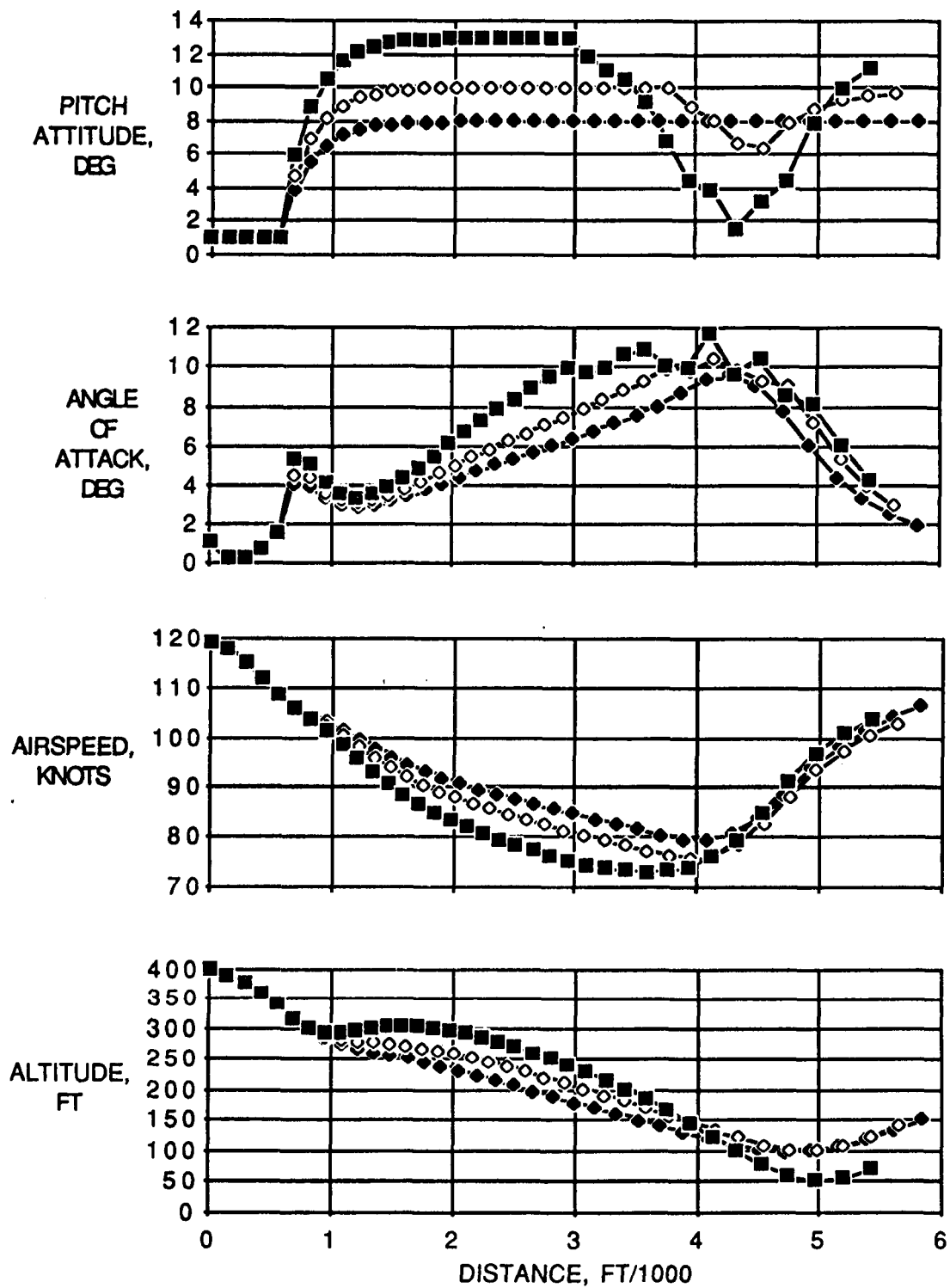


Figure 9 Performance of the TP configuration in landing approach microburst encounters.



## **Session II, Airborne-Hazard Definition**

**11 July 1988 Weather and Resulting TDWR Alarms at Denver, Colorado  
Wayne Sand, NCAR**

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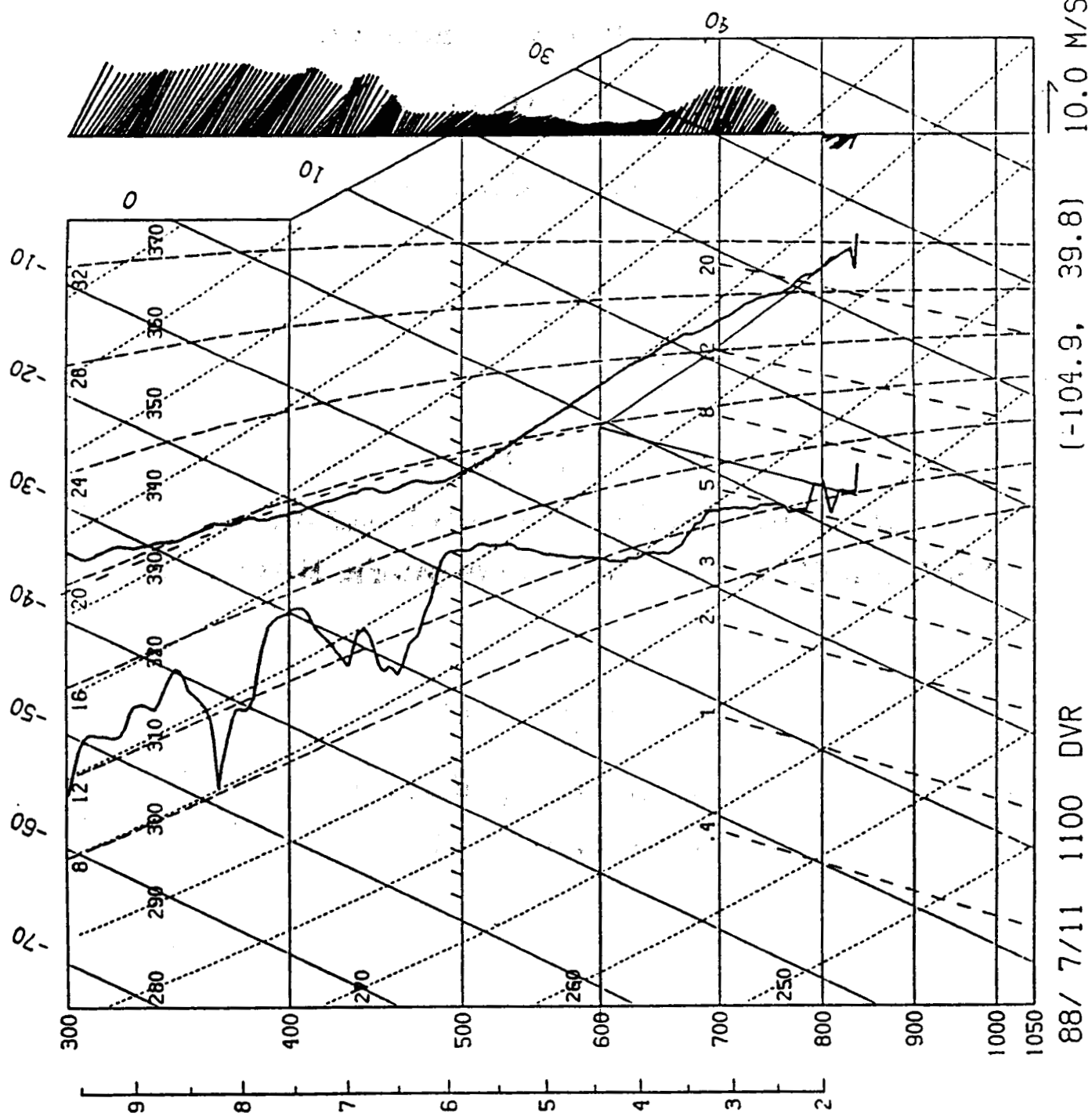
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at Denver, Colorado**

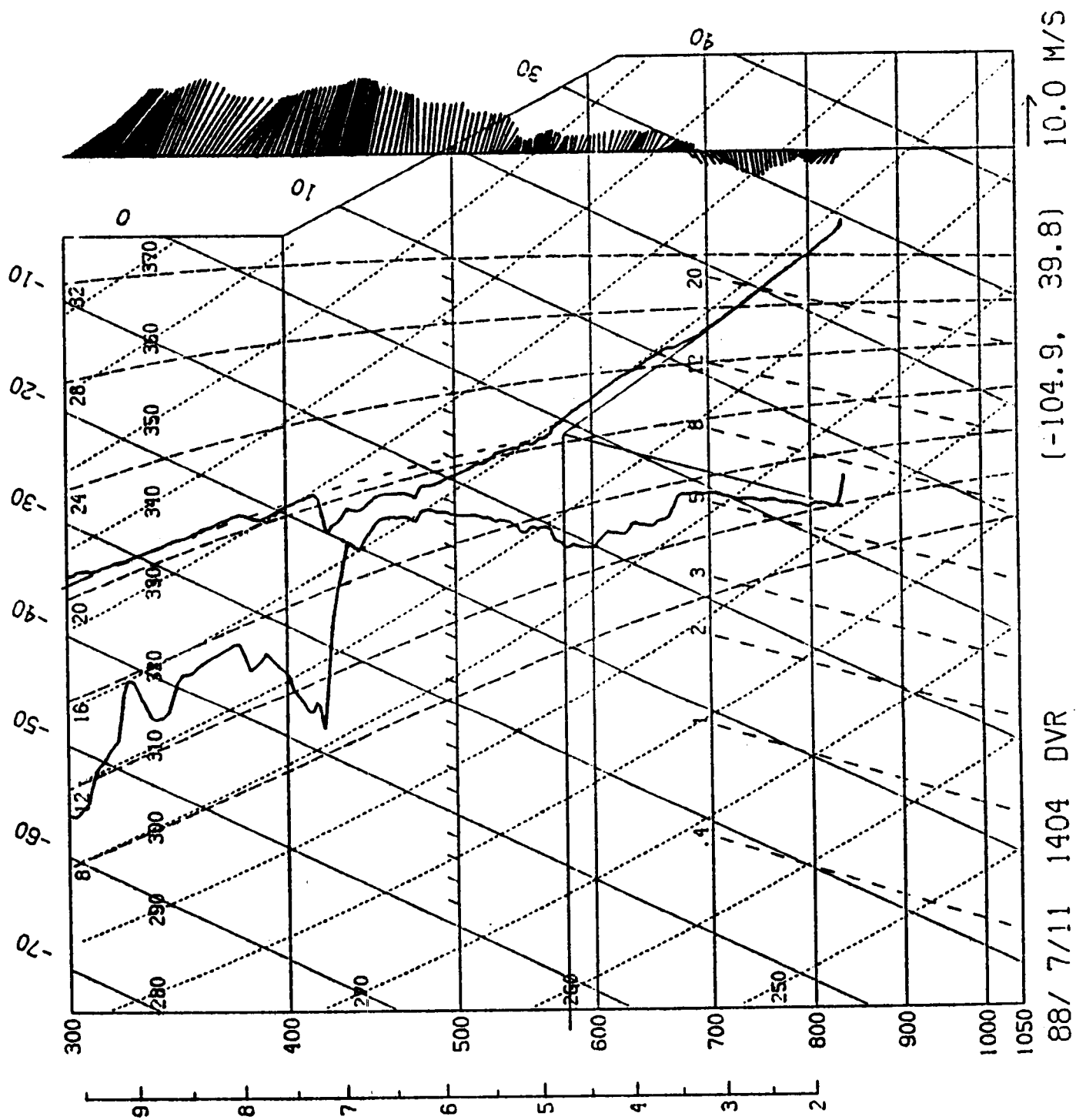
**by**

**Wayne Sand  
Research Applications Program  
National Center for Atmospheric Research**

**Presented at:**

**Williamsburg, Virginia  
18-20 October 1988**





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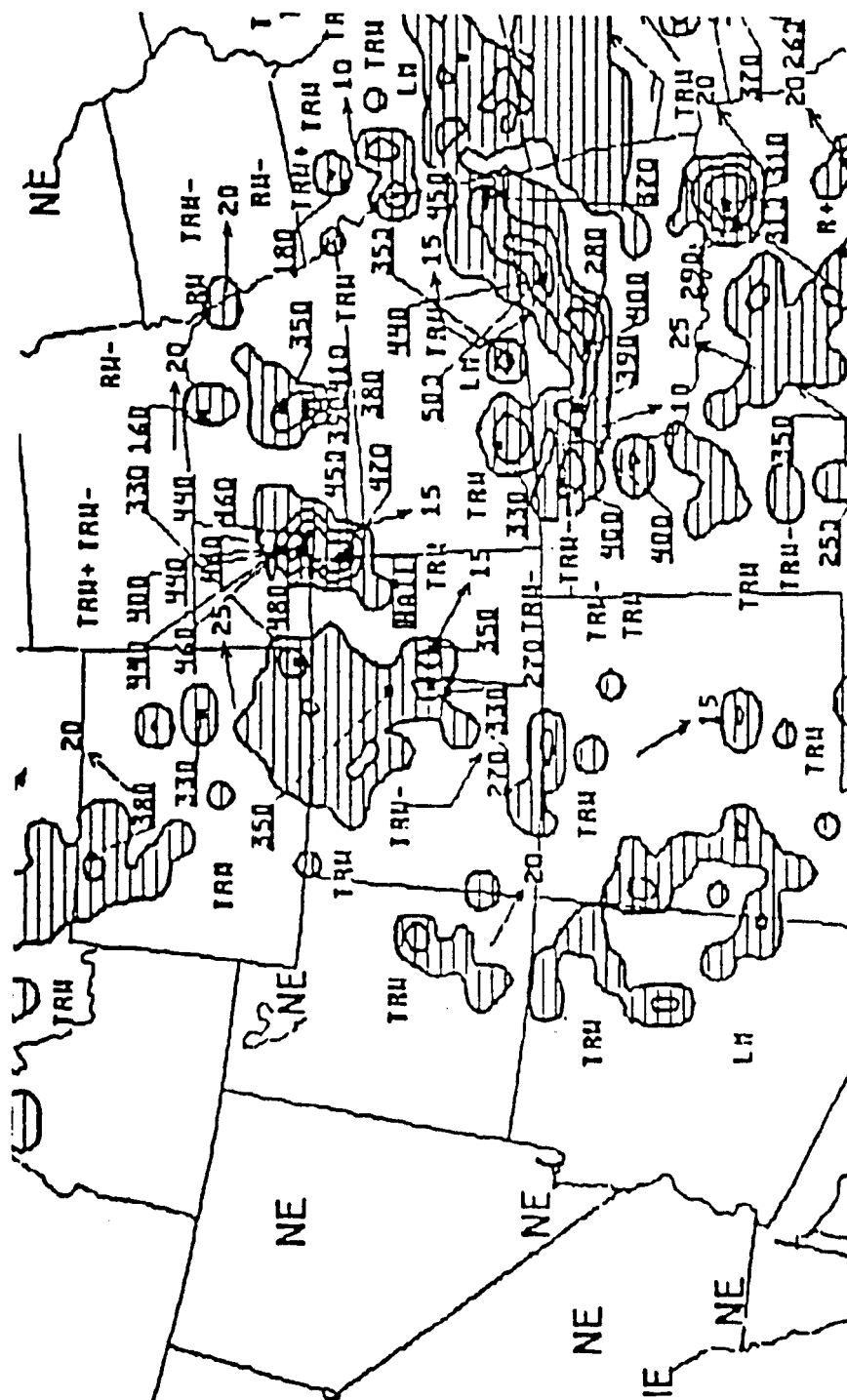
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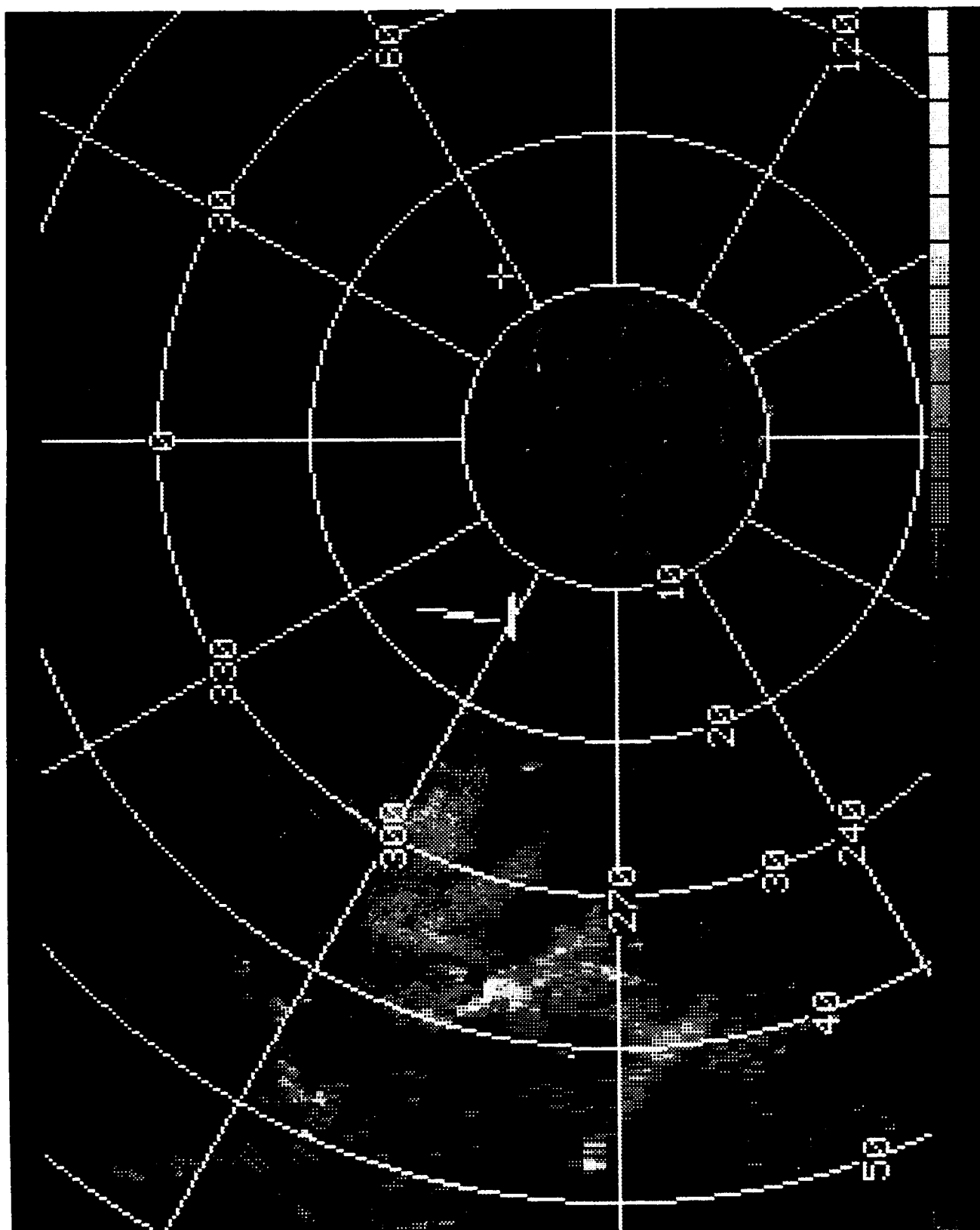
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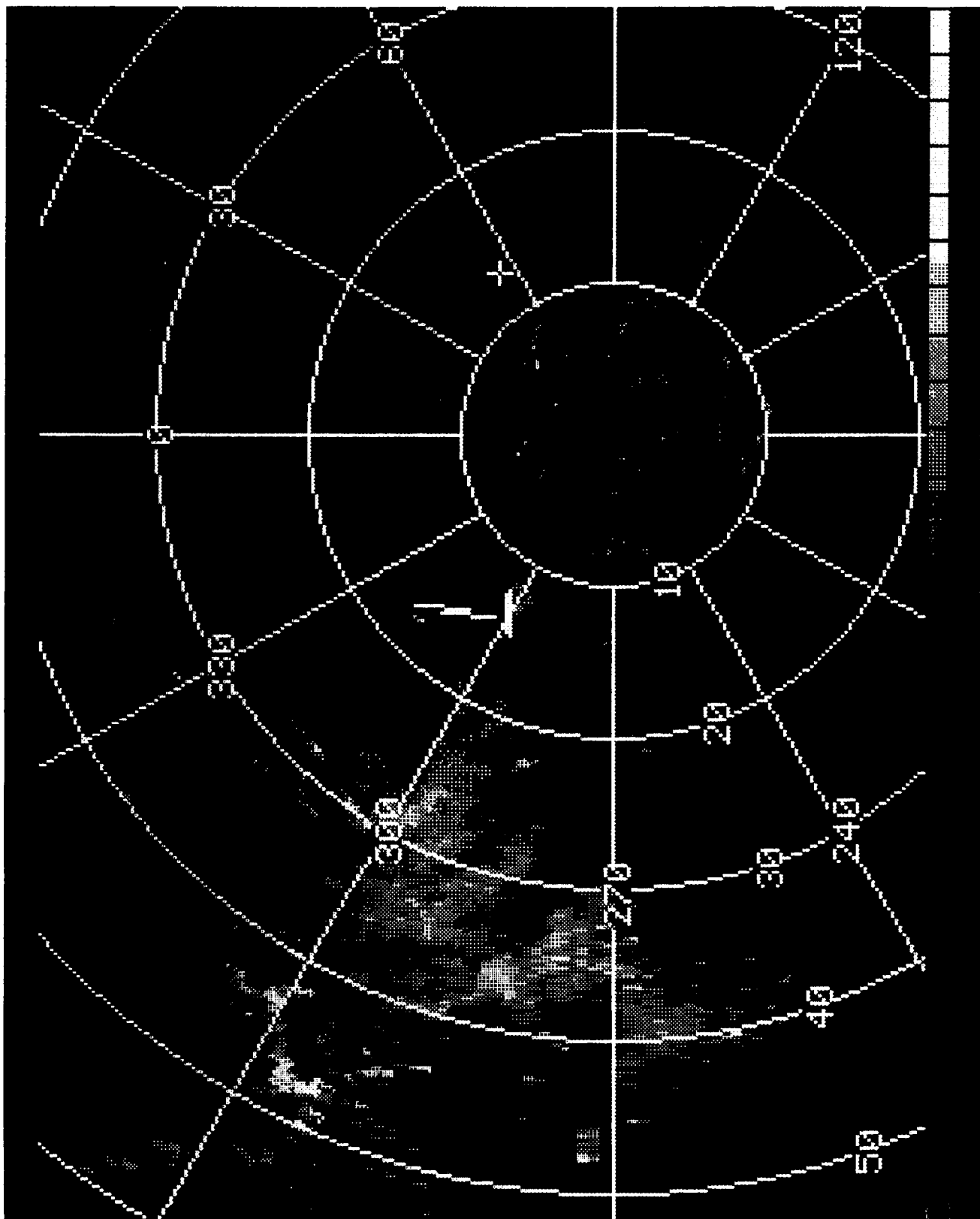
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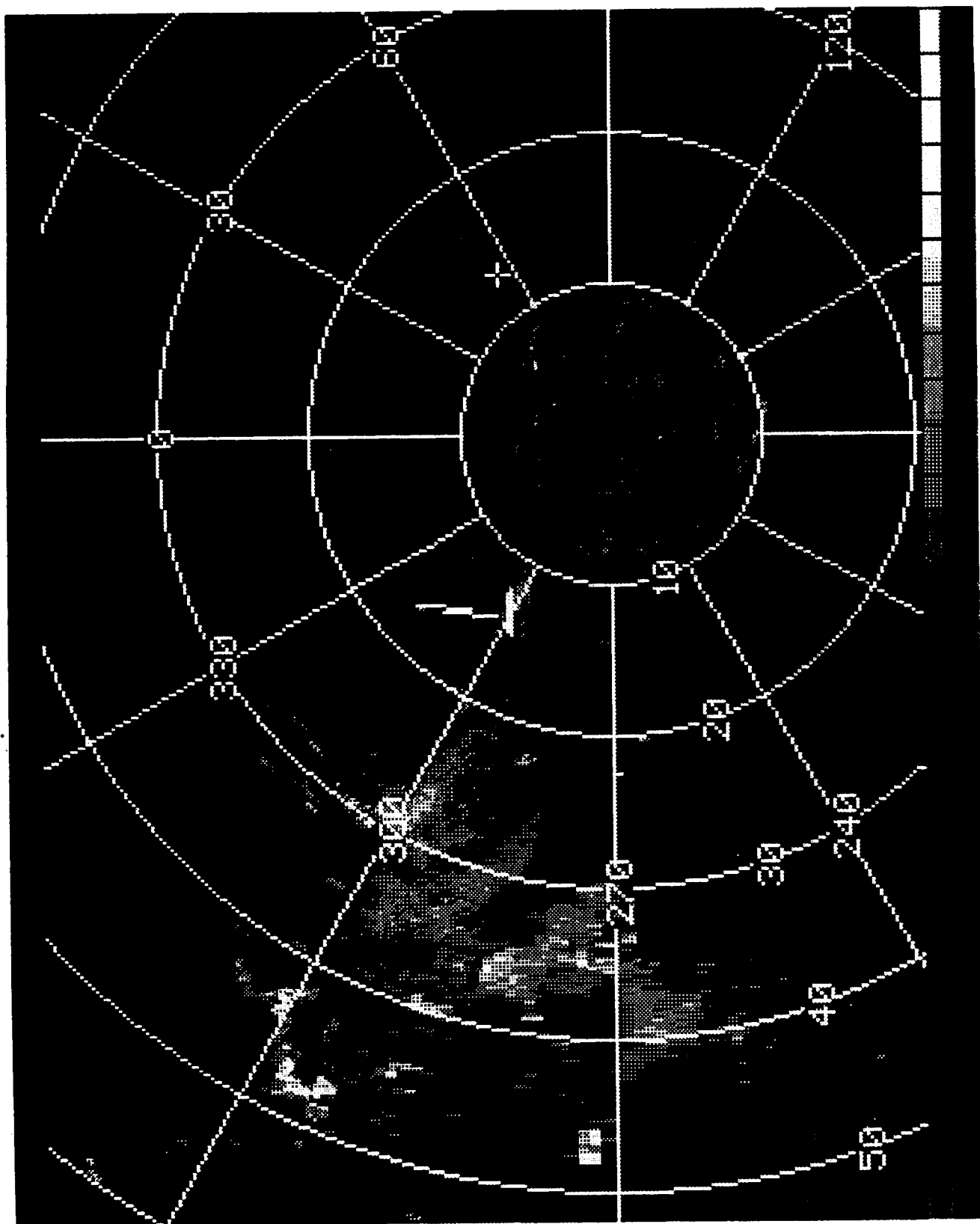
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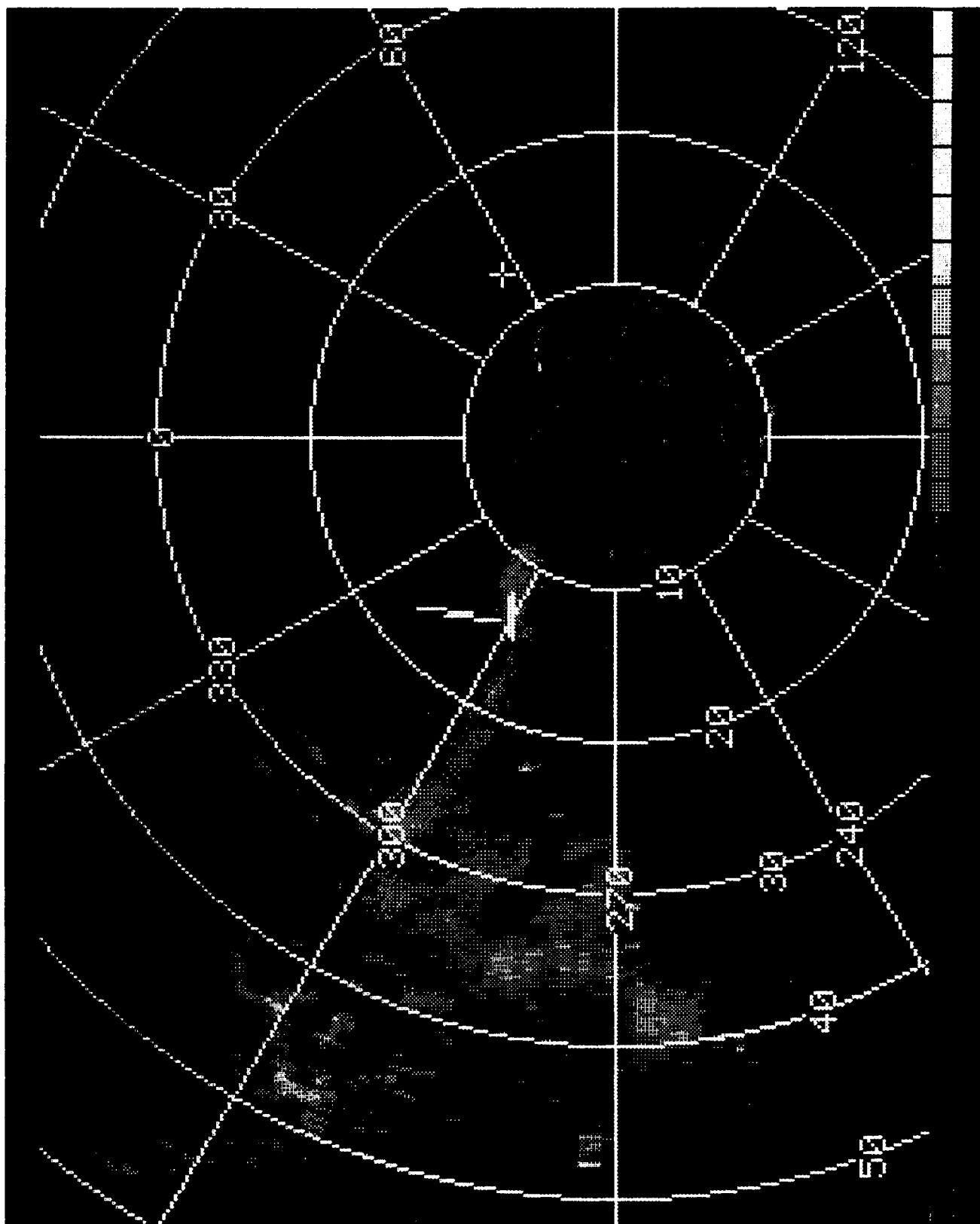


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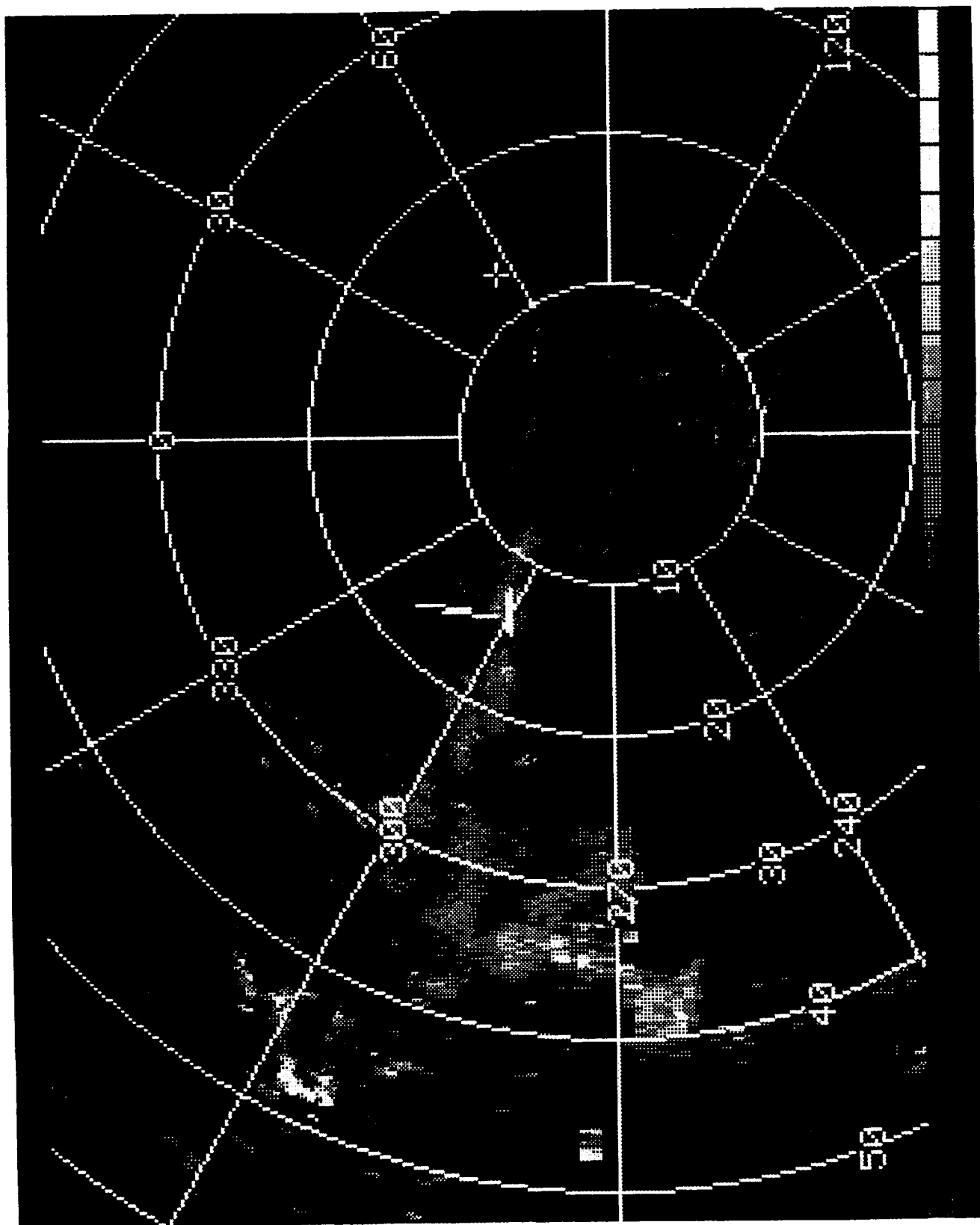
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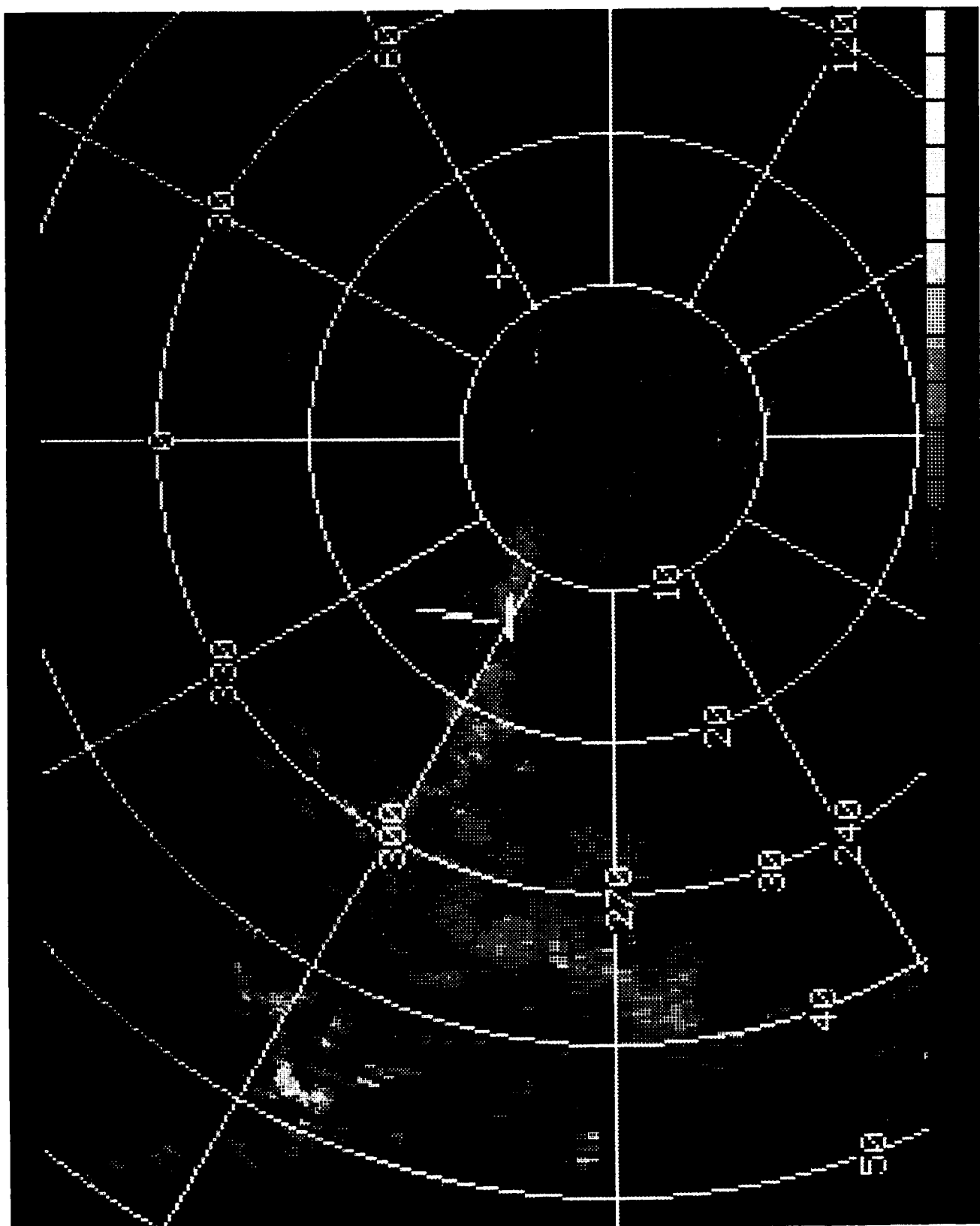


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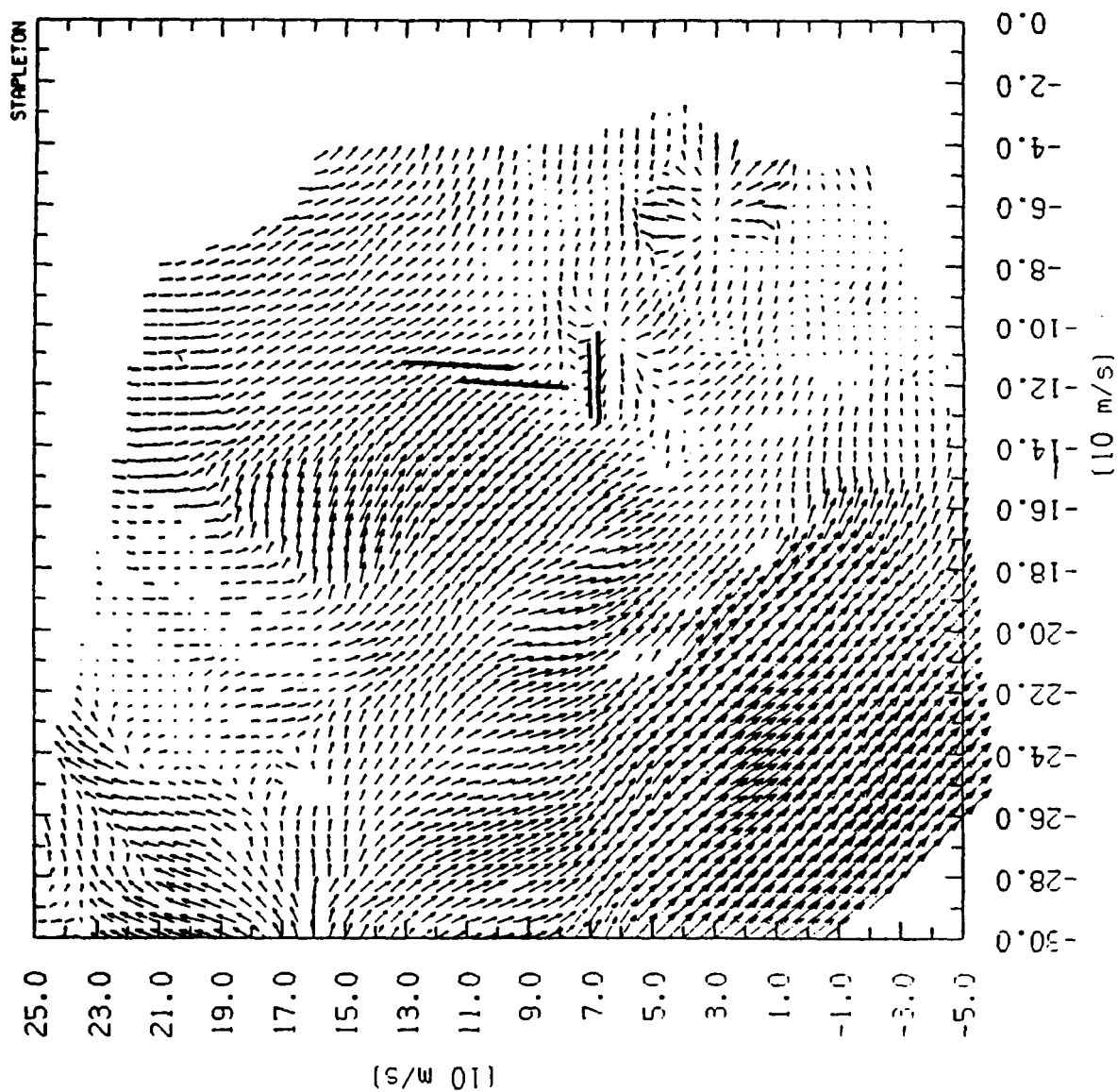


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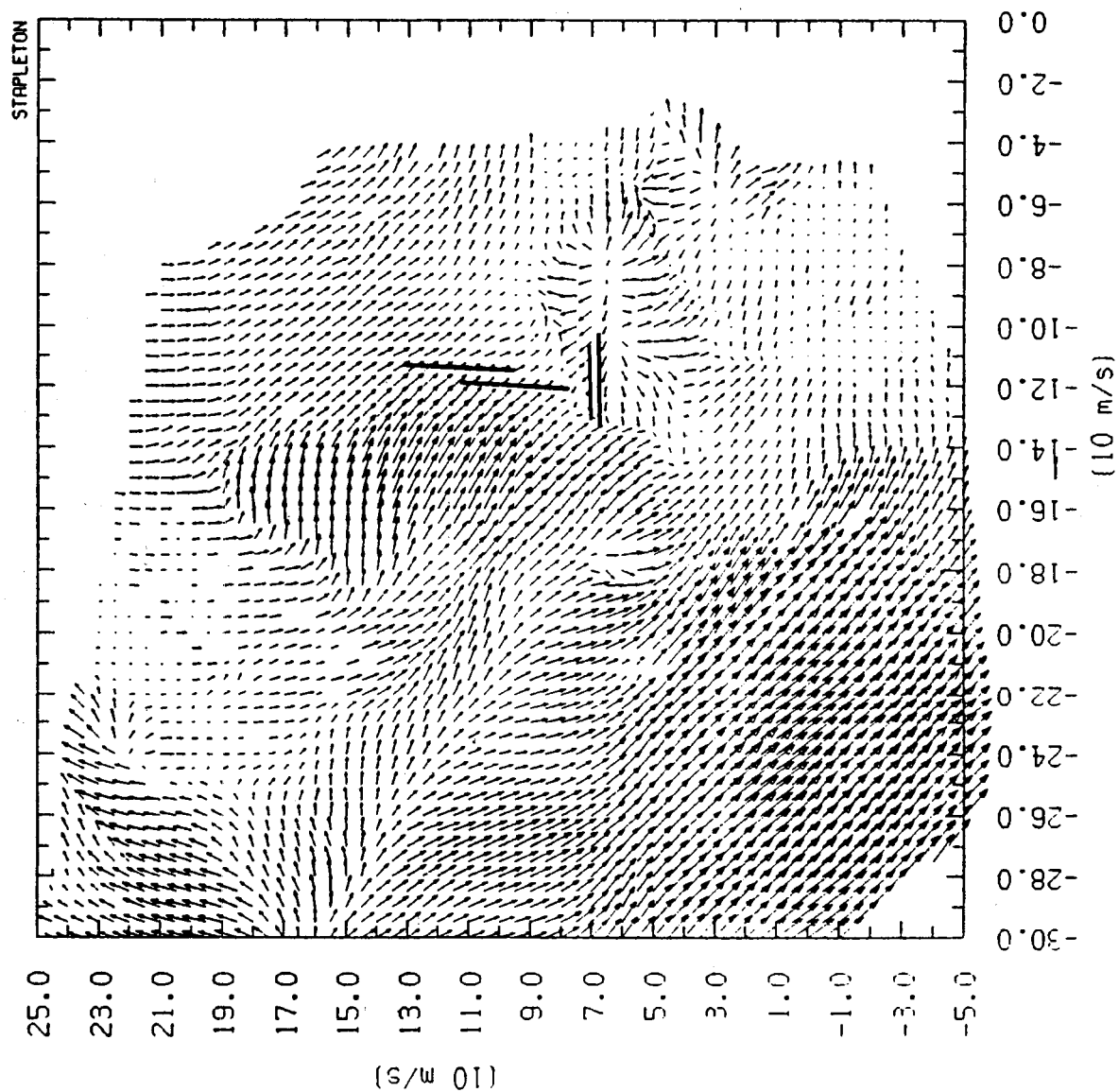
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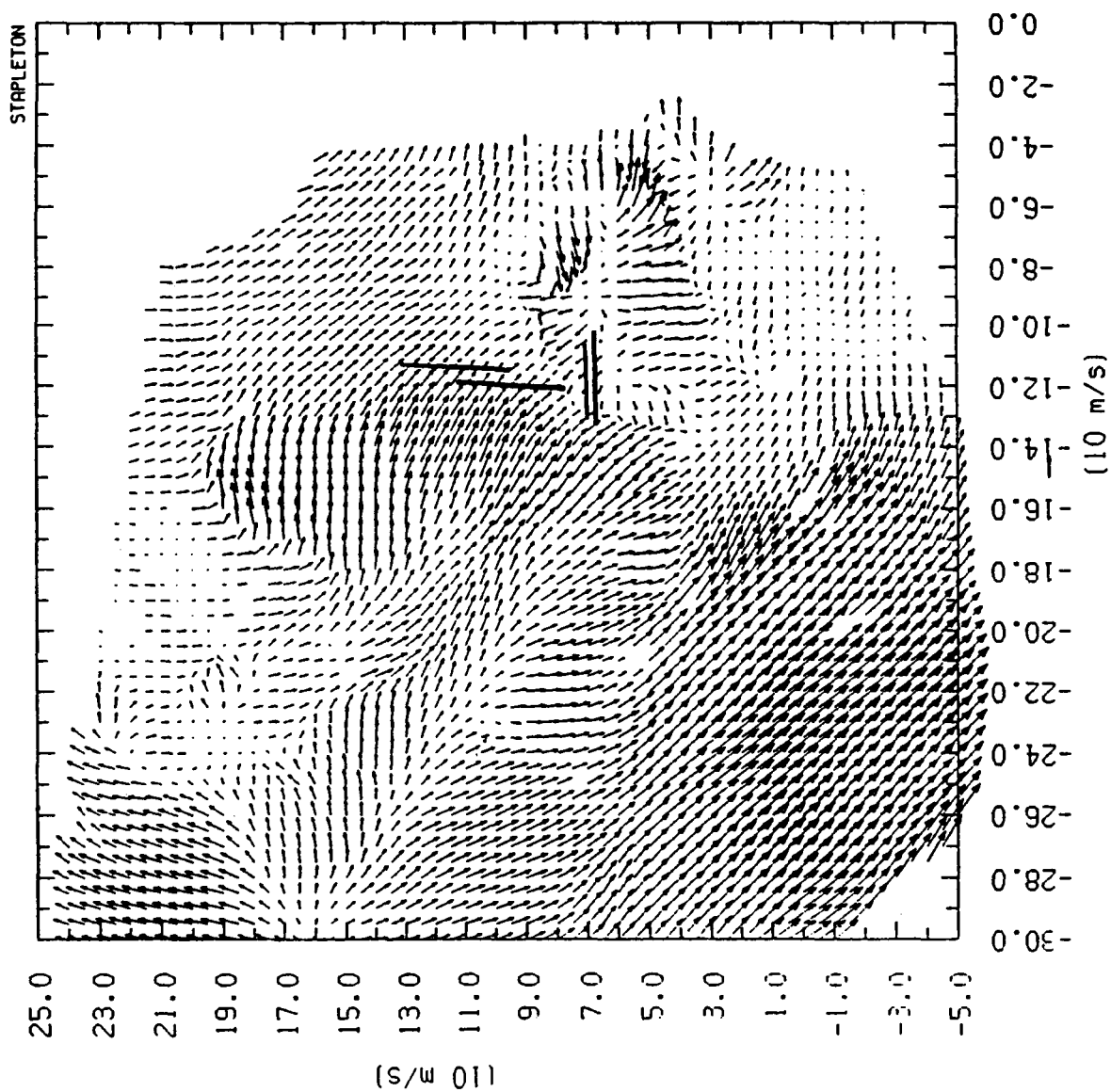
UND = (-2.74, 20.55 )



# VELOCITY FIELD

FL2 = ( 0.00, 0.00 )      TIME = 88    7 11 22 10    3

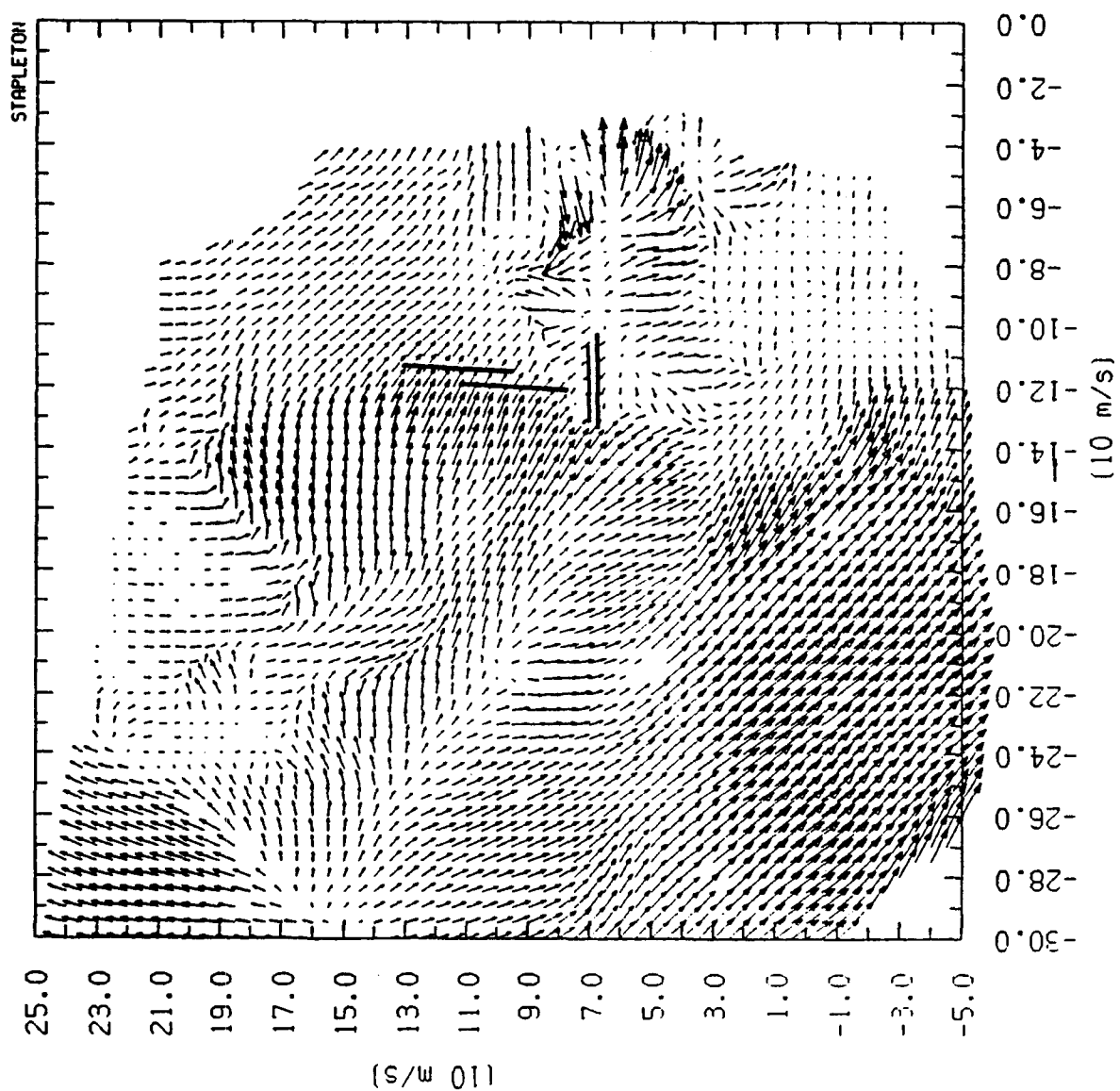
UND = (-2.74, 20.55 )



# VELOCITY FIELD

FL2 = ( 0.00, 0.00 )      TIME = 88 7 11 22 11 58

UND = (-2.74, 20.55 )



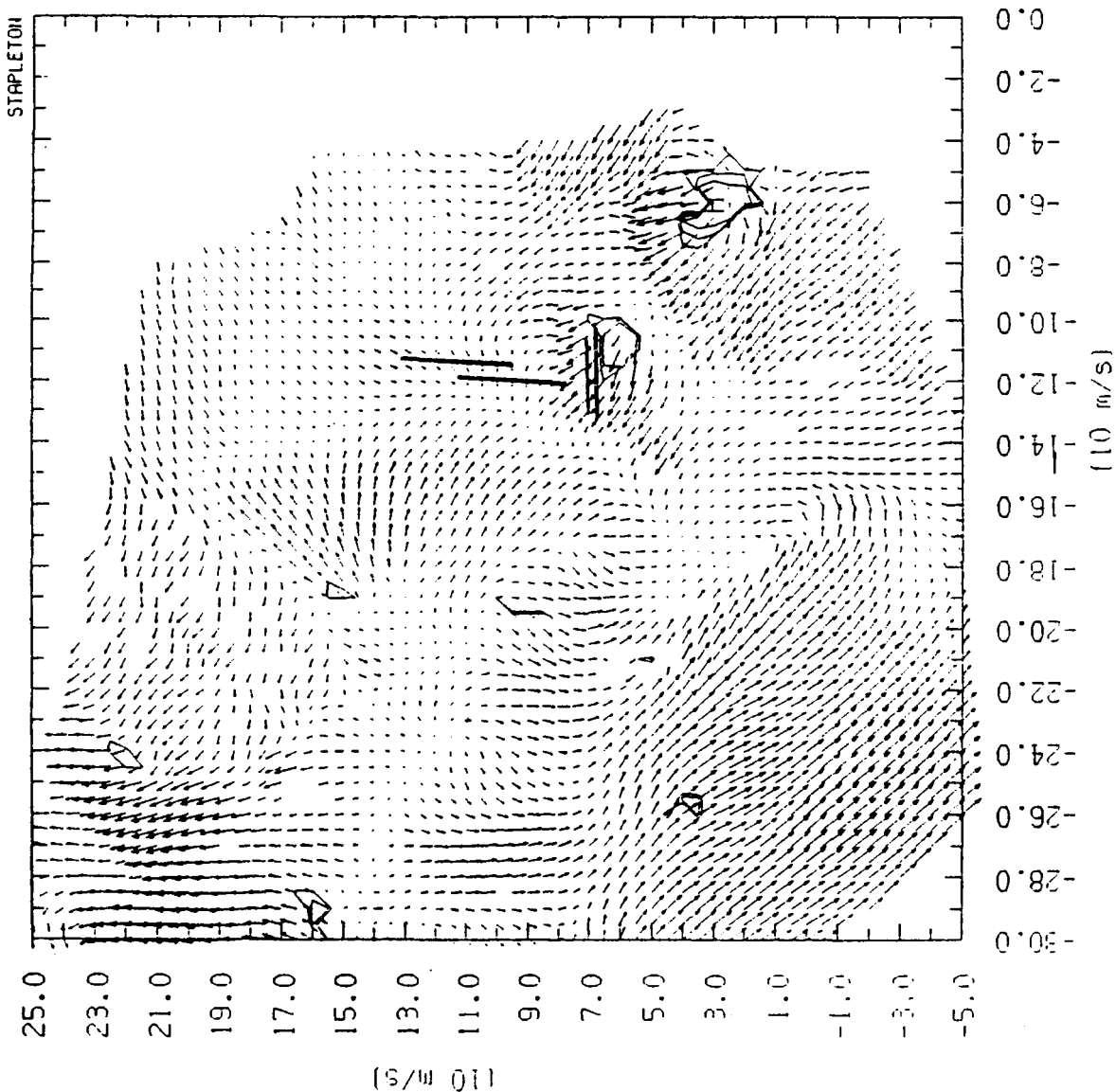


# EDDY FIELD(WITH VELOCITY DIFFERENCE BY SEARCH OVERLAY)

FL2 = ( 0.00, 0.00 )      TIME = 88 7 11 22 6 2

UND = (-2.74, 20.55 )      REMOVED VECT. = (4.84, -4.86)

H = 17.31

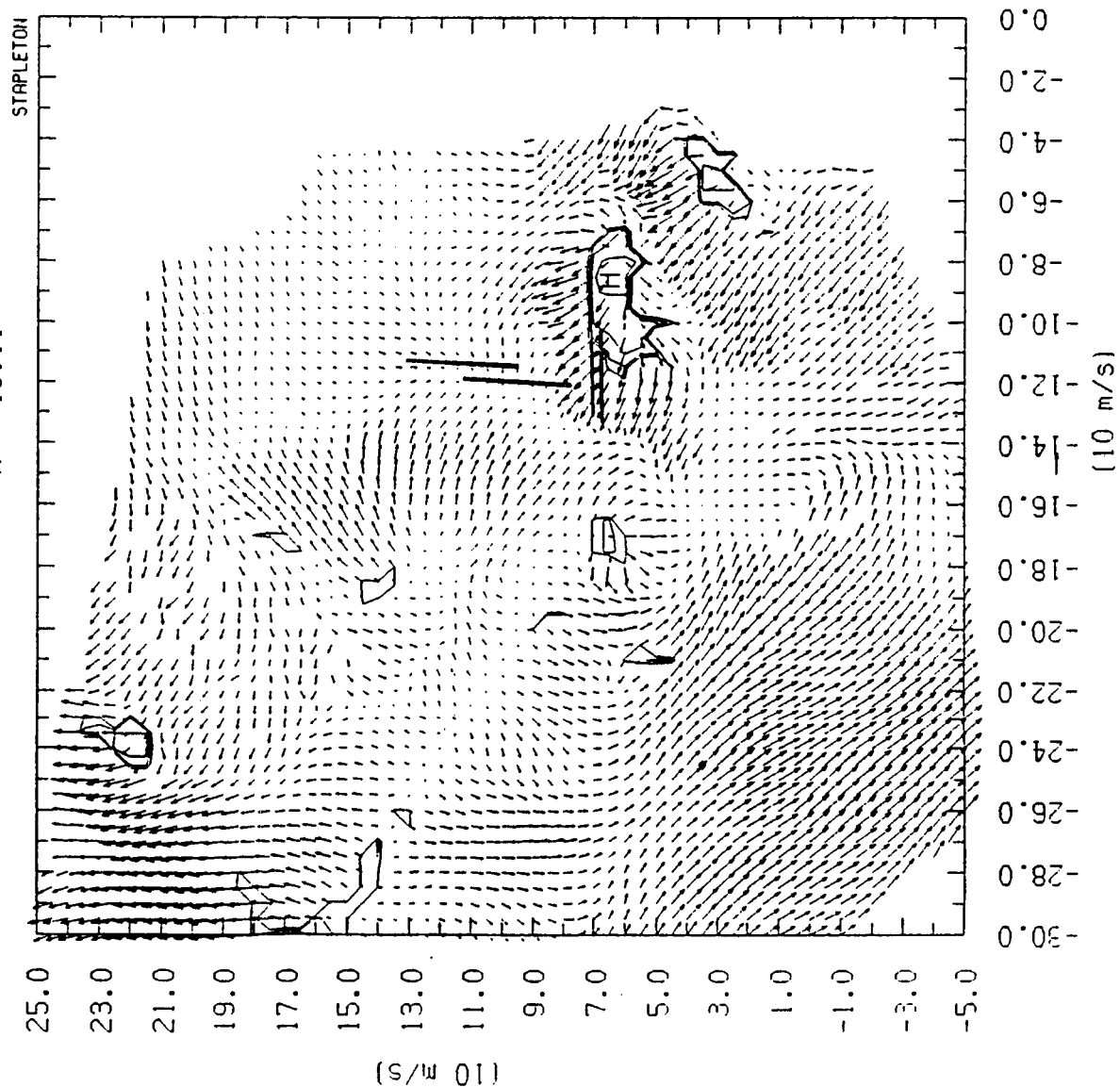


# EDDY FIELD(WITH VELOCITY DIFFERENCE BY SEARCH OVERLAY)

FL2 = ( 0.00, 0.00 )      TIME = 88 7 11 22 8 3

UND = (-2.74, 20.55 )      REMOVED VECT. = (5.10, -4.64)

H = 18.11

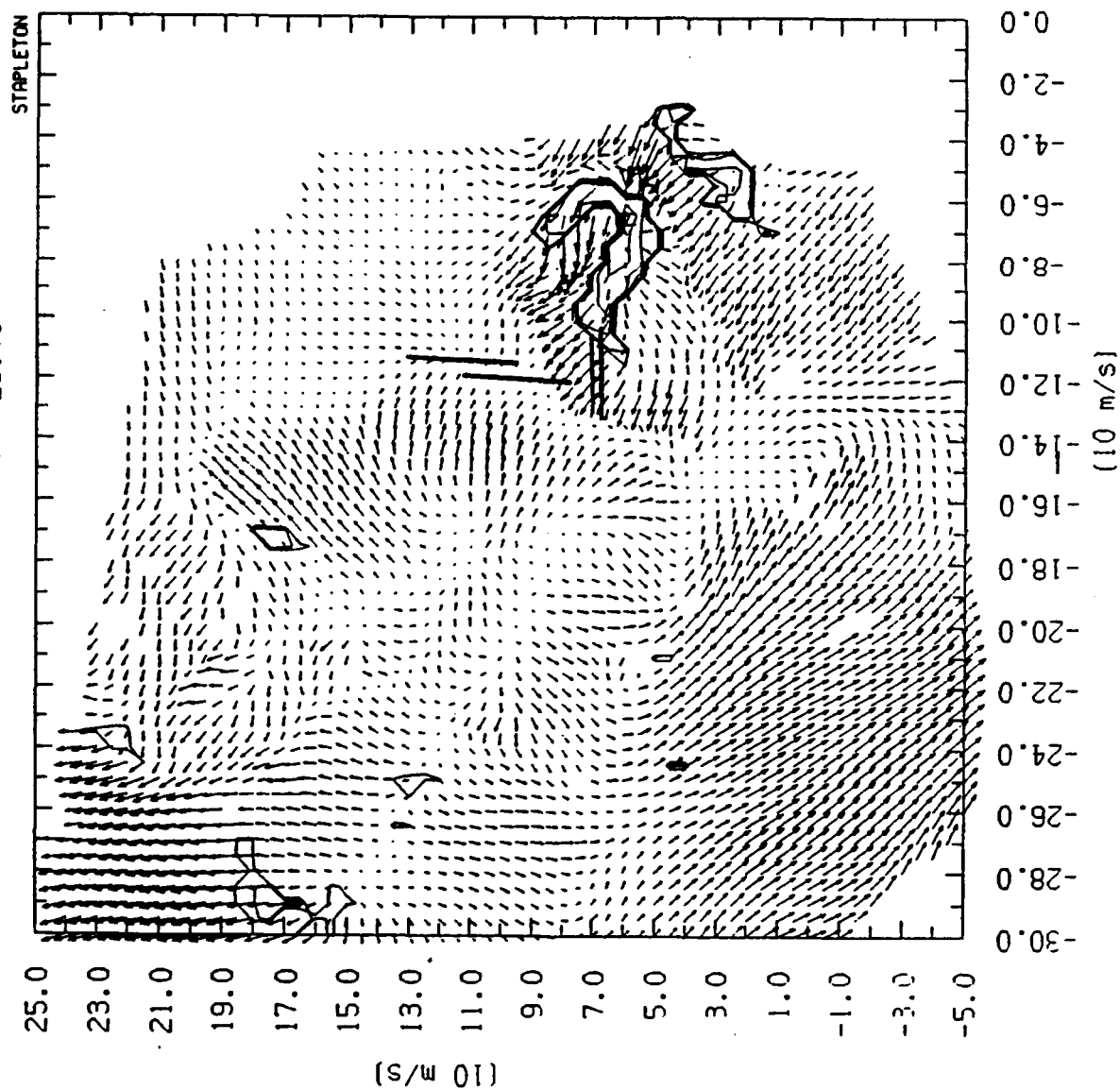


# EDDY FIELD(WITH VELOCITY DIFFERENCE BY SEARCH OVERLAY)

FL2 = ( 0.00, 0.00 )      TIME = 88 7 11 22 10 3

UND = (-2.74, 20.55 )      REMOVED VECT. = (5.24, -4.66)

H = 23.79

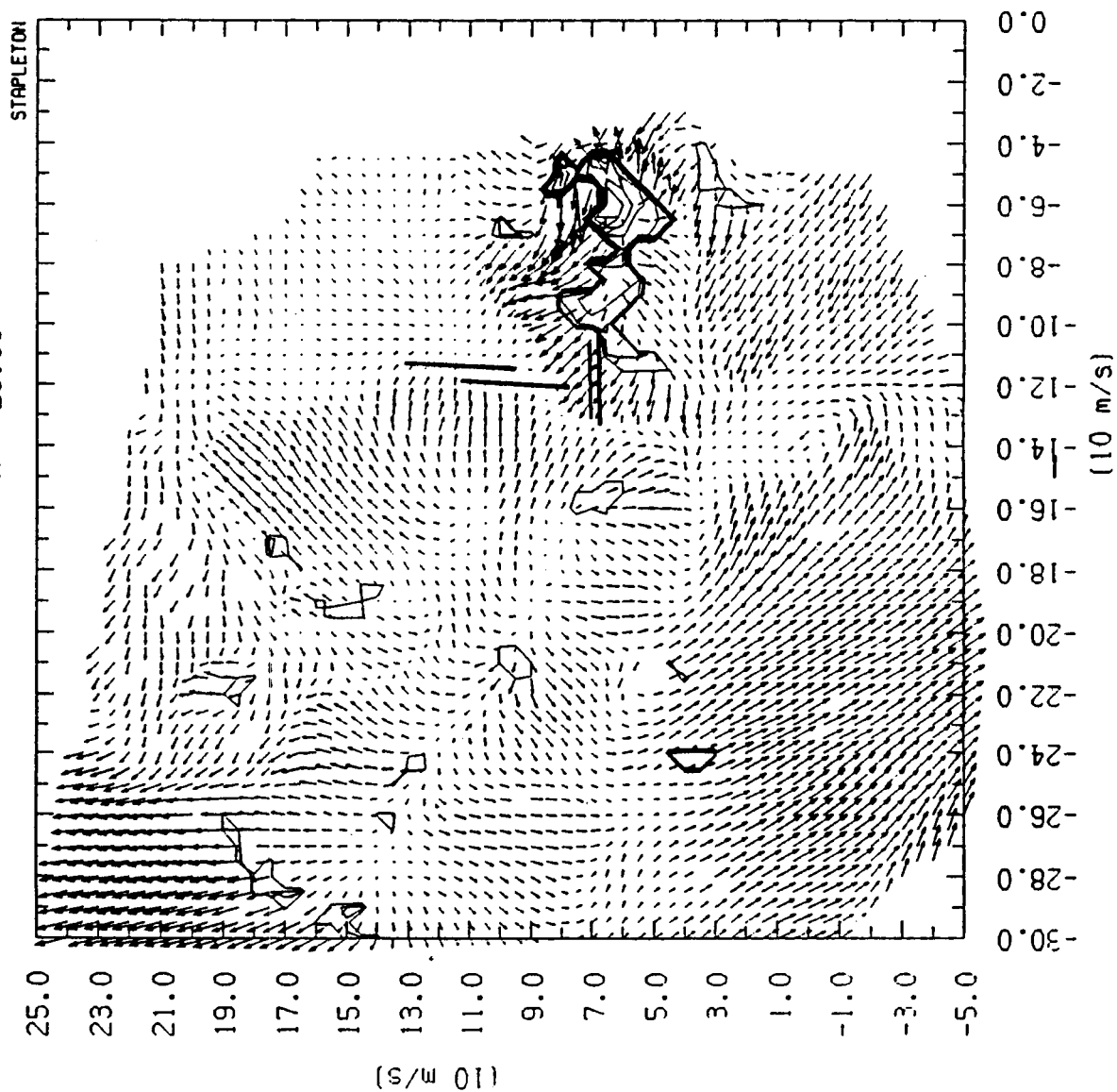


# EDDY FIELD(WITH VELOCITY DIFFERENCE BY SEARCH OVERLAY)

FL2 = ( 0.00, 0.00 )      TIME = 88 7 11 22 11 58

UND = (-2.74, 20.55 )      REMOVED VECT. = (5.52, -4.43)

H = 29.90



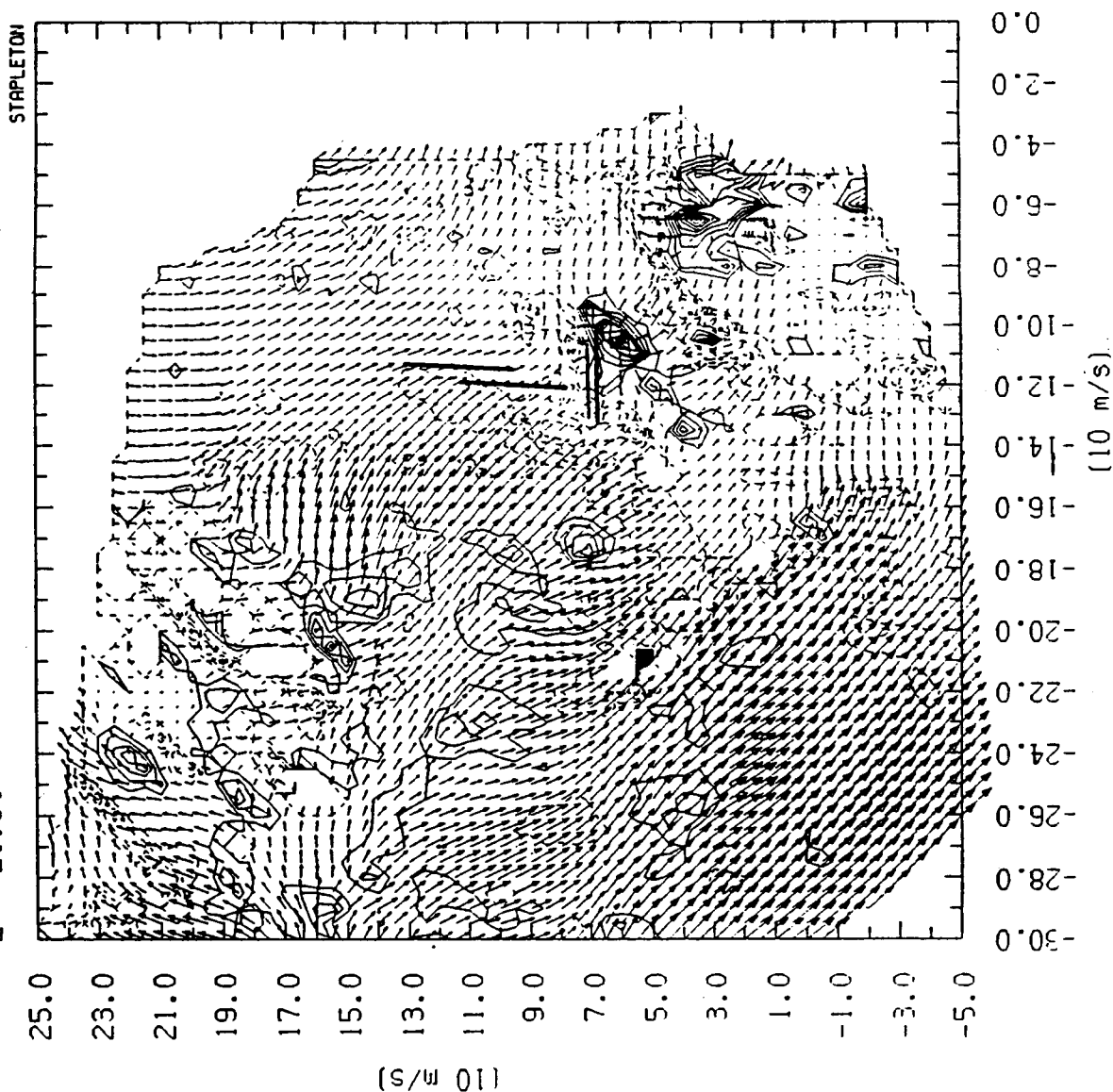
# VELOCITY FIELD(WITH DIVERGENCE OVERLAY)

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UND = (-2.74, 20.55 )

L = -21.94

H = 27.48



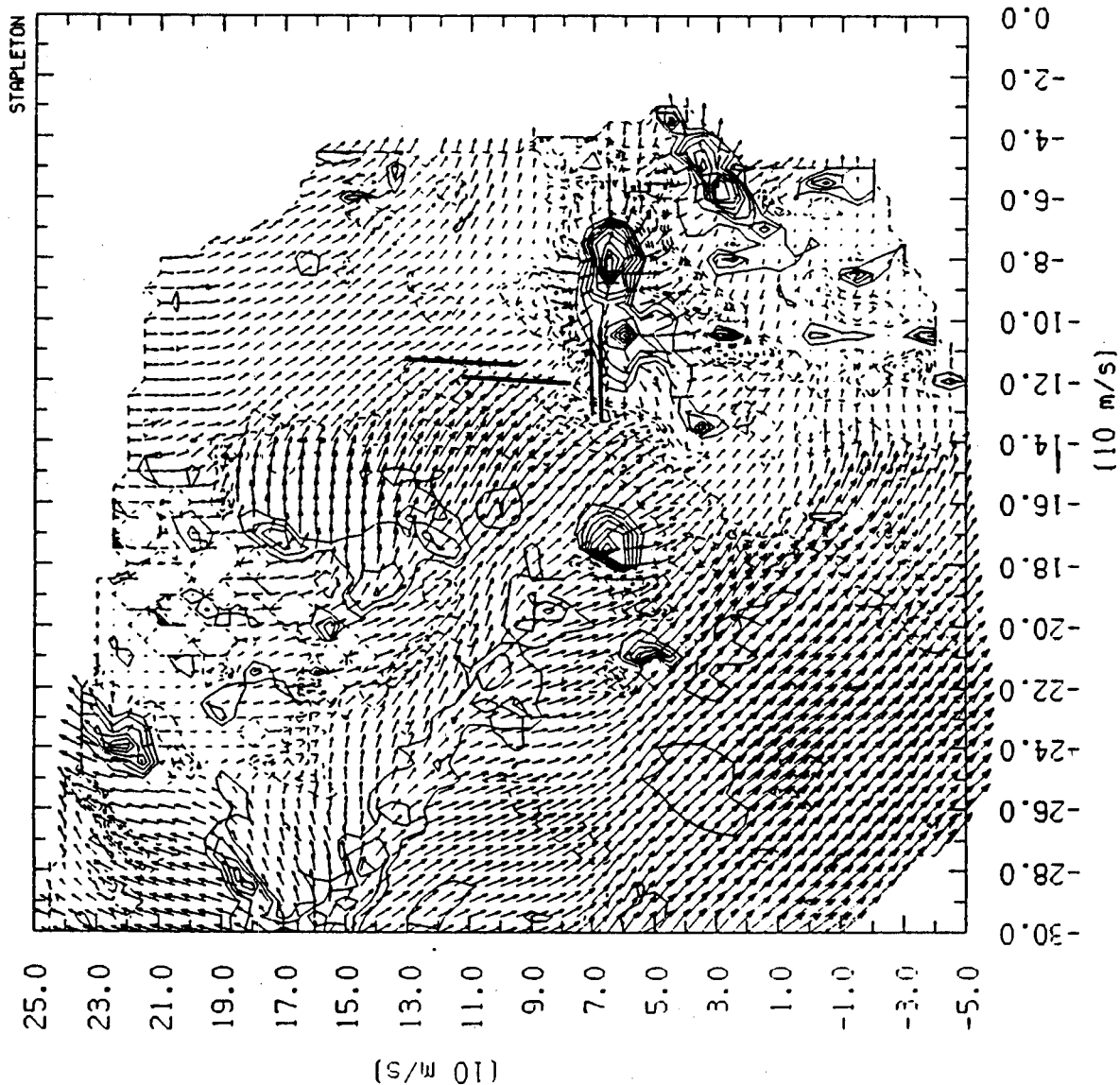
# VELOCITY FIELD(WITH DIVERGENCE OVERLAY)

FL2 = ( 0.00, 0.00 )      TIME = 88 7 11 22 8 3

UND = (-2.74, 20.55)

L = -22.27

H = 24.74



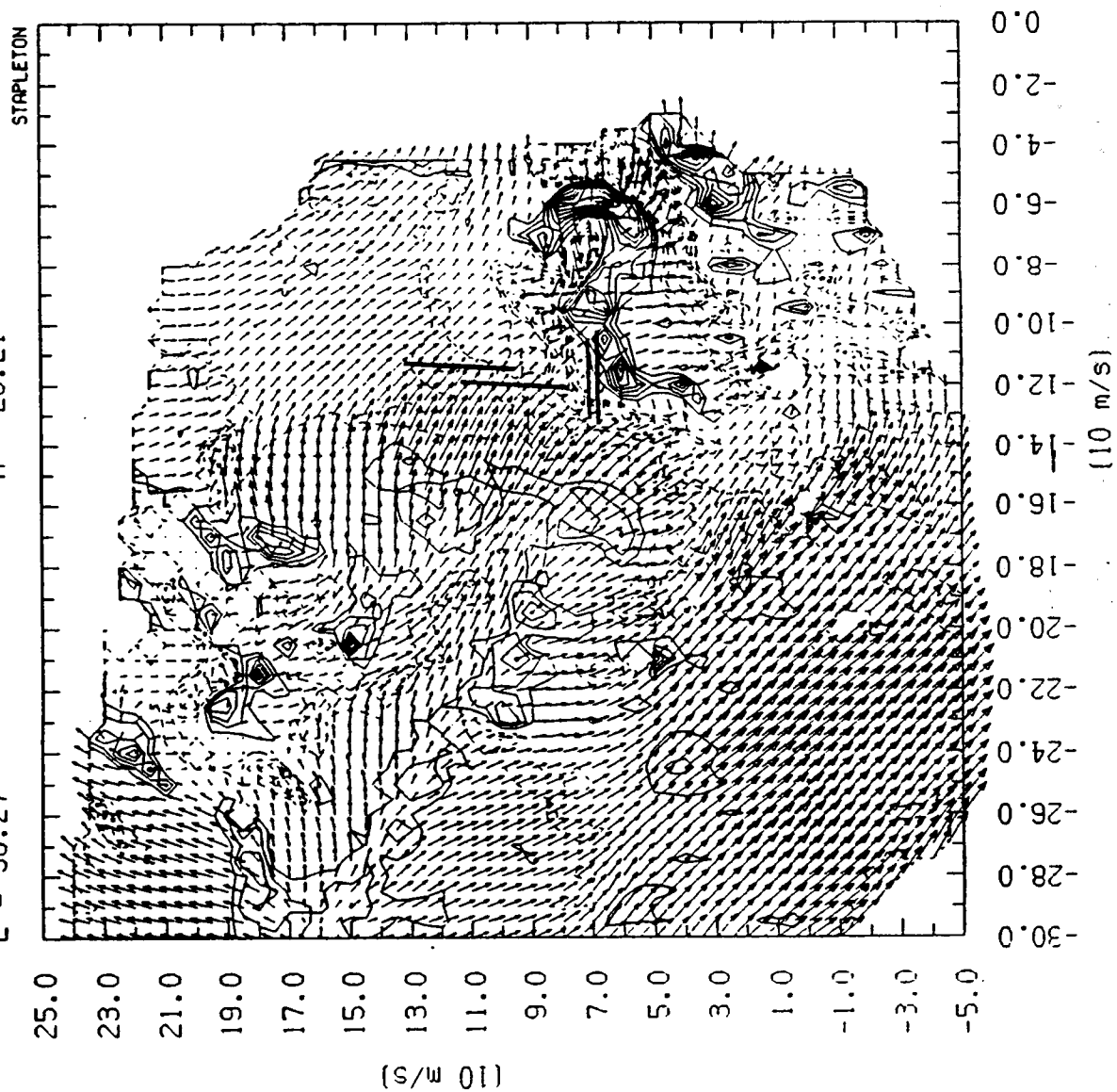
# VELOCITY FIELD(WITH DIVERGENCE OVERLAY)

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UND = (-2.74, 20.55 )

L = -36.27

H = 26.21



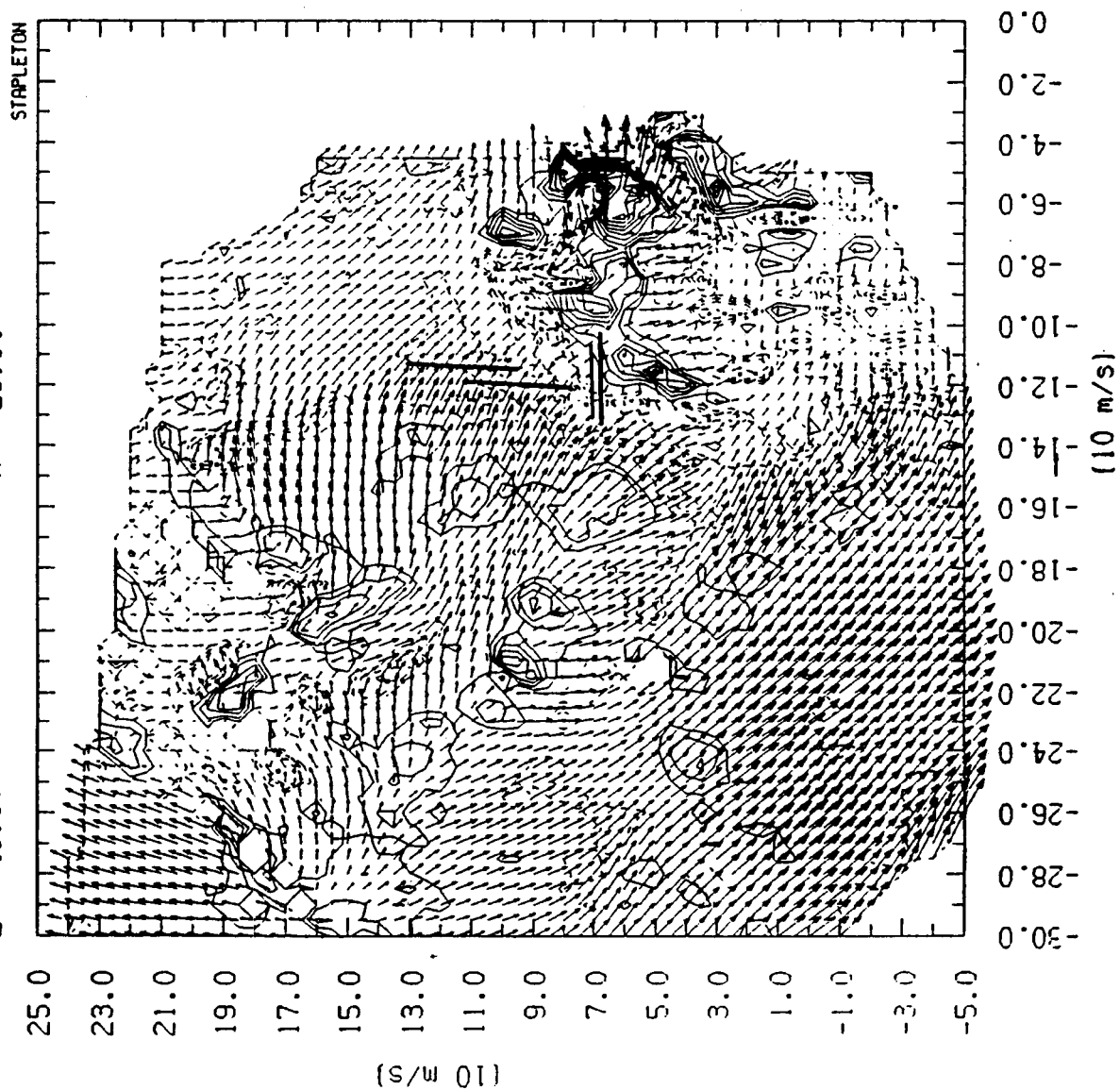
# VELOCITY FIELD(WITH DIVERGENCE OVERLAY)

FL2 = ( 0.00, 0.00 )      TIME = 88   7 11 22 11 58

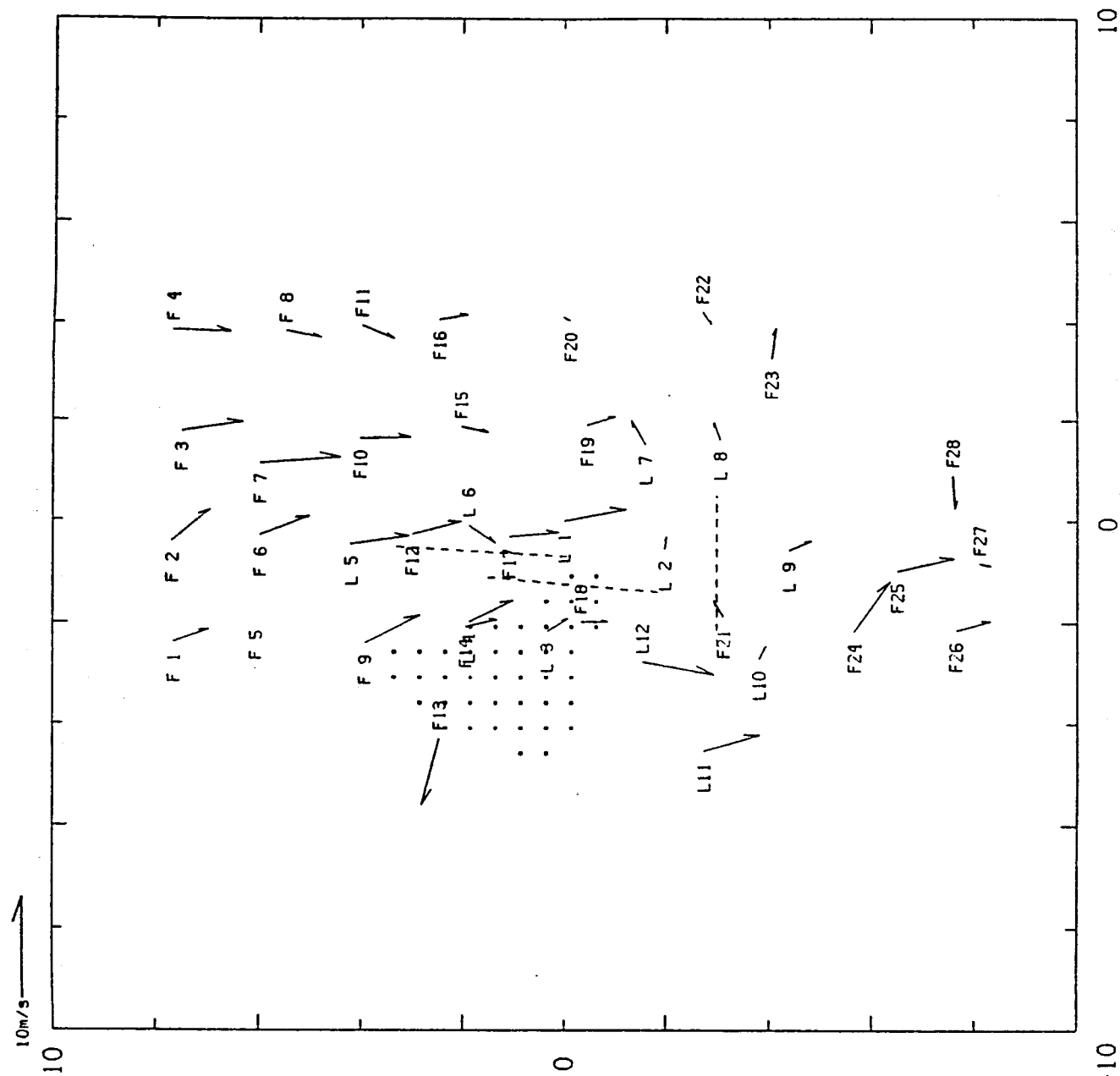
UND = (-2.74, 20.55 )

L = -45.07

H = 26.64

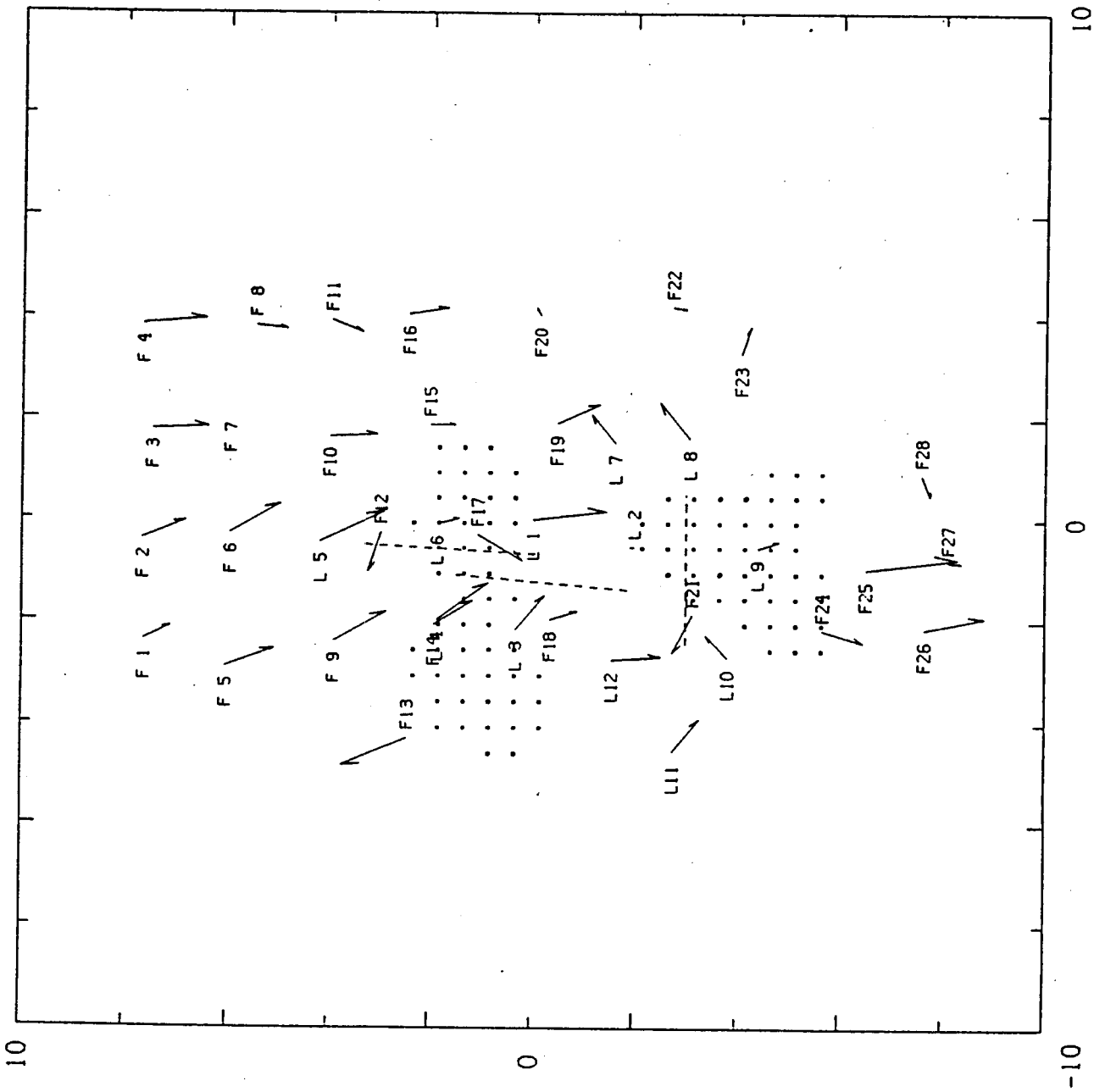




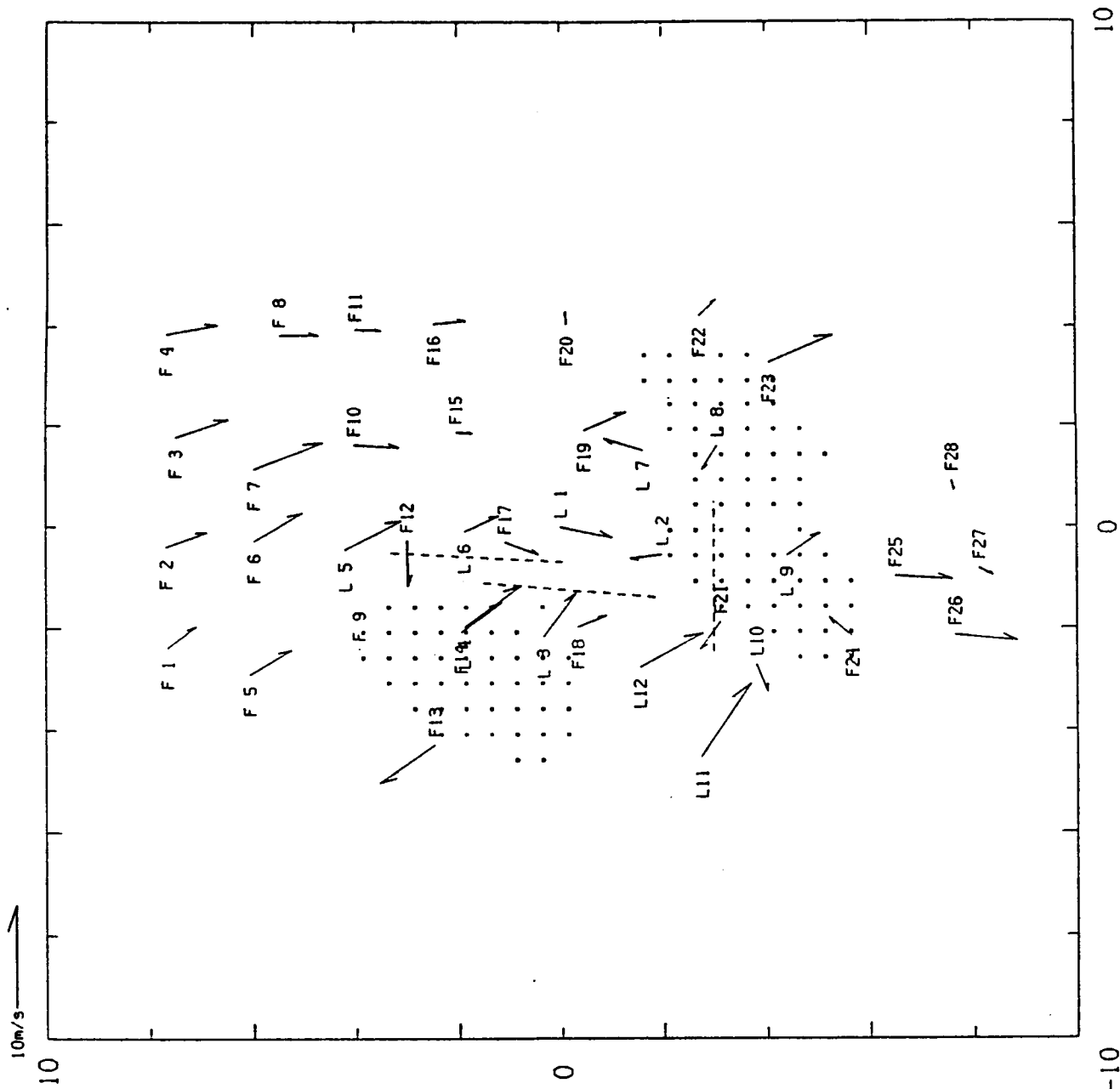


88/07/11-22:08:00 LLWAS-FLOWS MESONET (km x km)

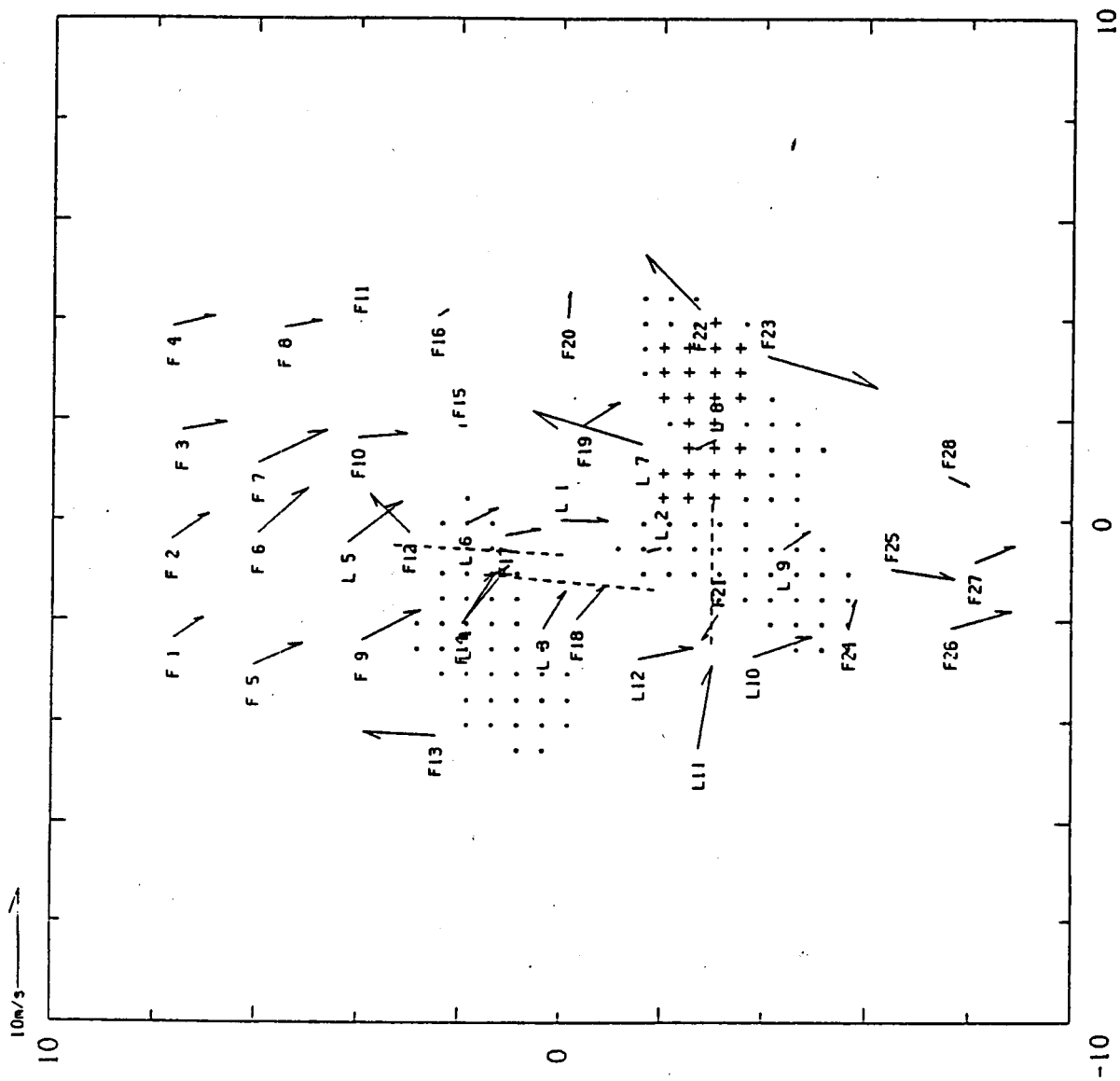
10m/s →



88/07/11-22:10:00 LLWAS-FLOWS MESONET (km x km)



88/07/11-22:12:00 LLWAS-FLOWS MESONET (km x km)



# TDWR Alphanumeric Alarms

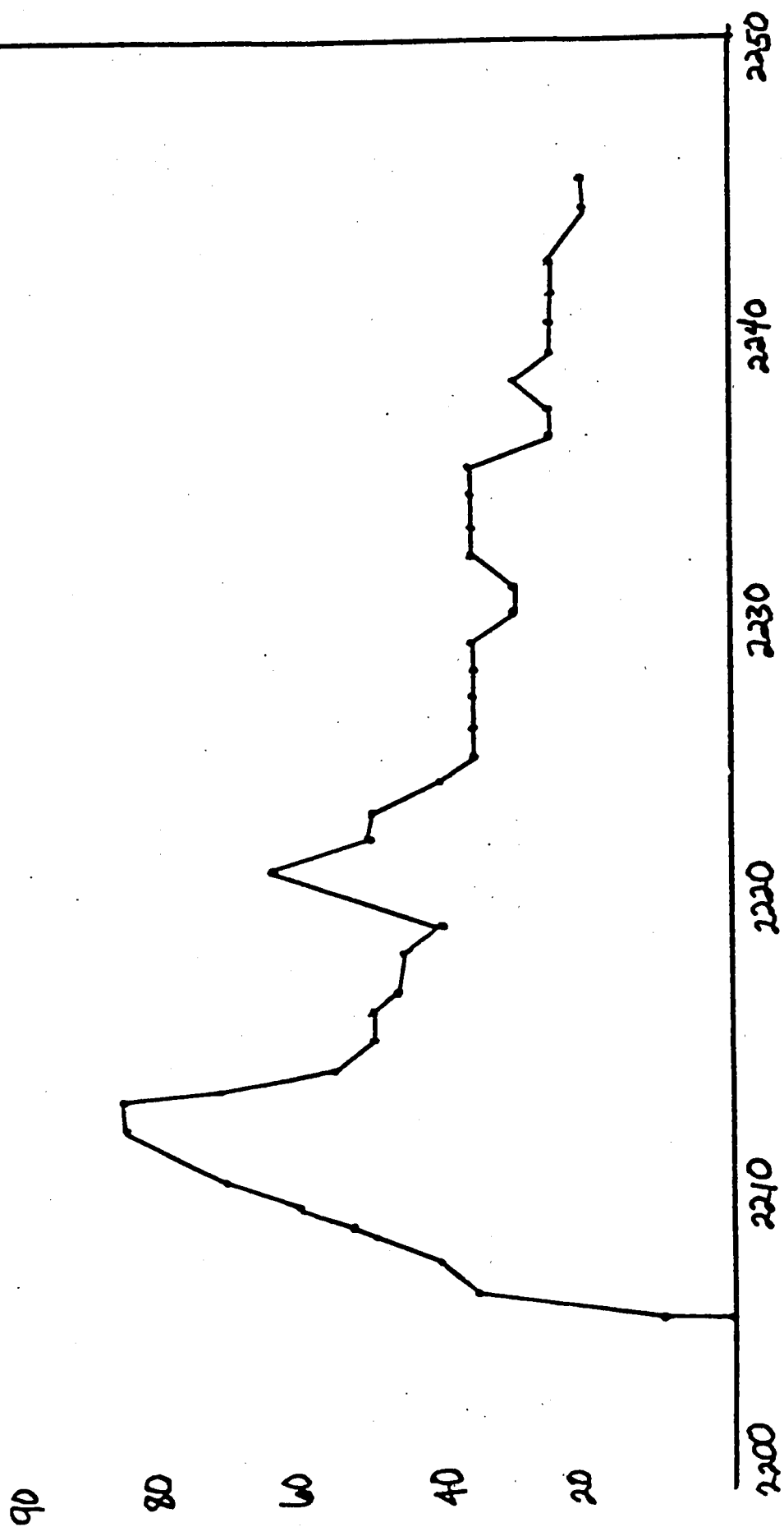
11 July 1988

## Runway 26 R/L Arrivals

<u>Time</u>	<u>Alarm</u>	<u>Threshold Winds</u>	<u>Expected Loss/Gain</u>	<u>Location</u>
22:05:43	WSA	240/04	10 kt gain	1 mile final
22:06:17	MBA	230/03	35 kt loss	1 mile final
22:07:17	MBA	220/09	40 kt loss	1 mile final
22:08:19	MBA	220/11	50 kt loss	2 mile final
22:09:35	MBA	110/05	60 kt loss	3 mile final
22:10:23	MBA	070/07	70 kt loss	3 mile final
22:11:17	MBA	090/03	80 kt loss	3 mile final
22:12:24	MBA	130/03	80 kt loss	3 mile final
22:13:25	MBA	130/03	85 kt loss	3 mile final

TDWR Detected Maximum  $\Delta V$

11 July 1988



NCAR GSD

RANGE

☐ 5m ☒ 15m ☐ 30m ☐ 50m

SCREEN

☒ 1 ☐ 2 ☐ 3 ☐ 4  
☐ 5 ☐ 6 ☐ 7 ☐ 8

MAPS

☐ Vortac & fixas  
☒ ASR rings  
☒ Airports  
☐ Interstates

PRECIPITATION LEVELS

☐ Off ☒ 1-6 ☐ 3-6 ☐ 5-6

WIND SHIFT:

☐ Off ☒ On

PRINT SCREEN:

☒ Print

STATUS: 2206

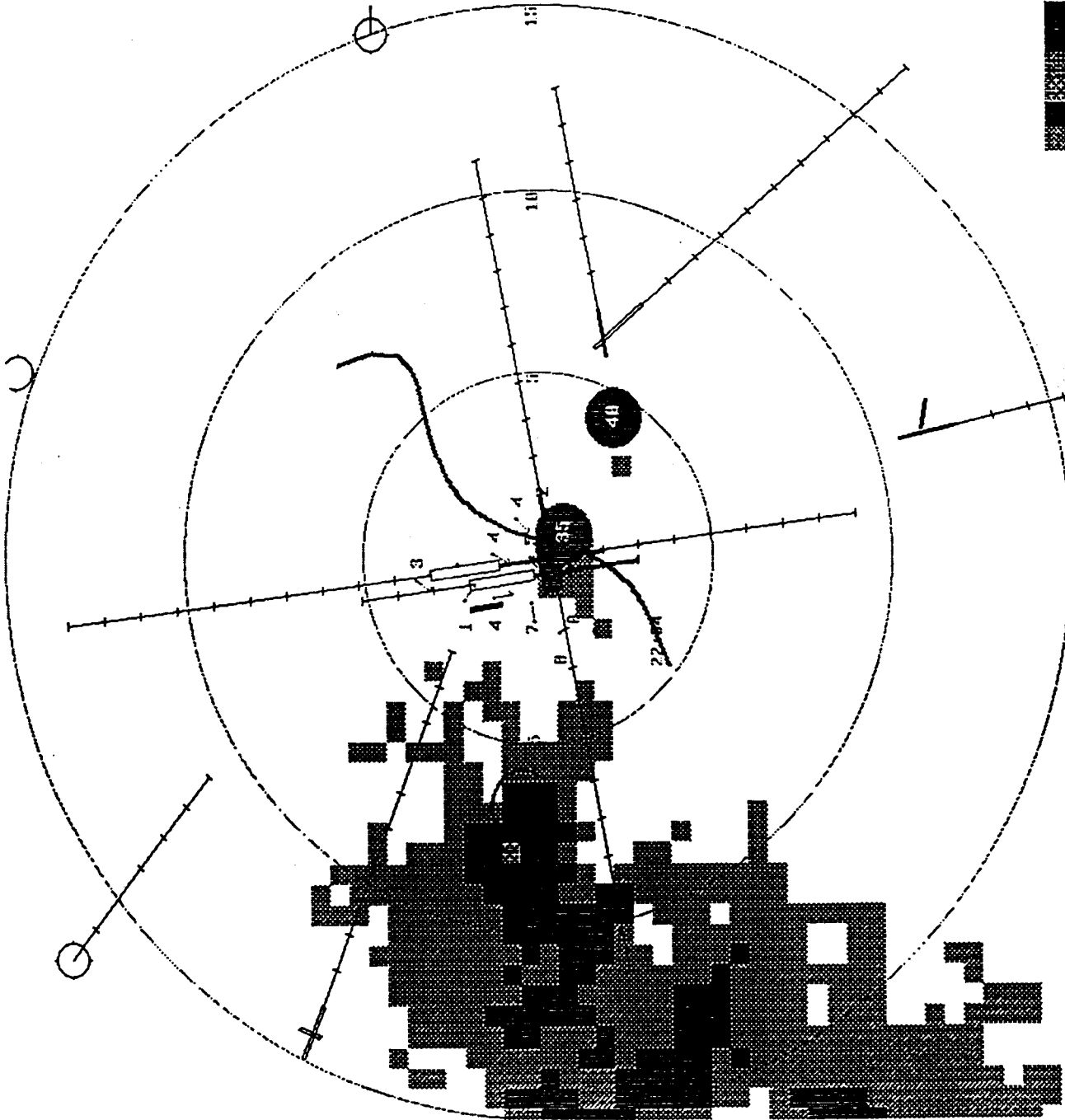
TIME:

MB: UP

GF: UP

PRECIP: UP

LLWAS: UP



NCAR GSD

RANGE

☐ 5m ☒ 15m ☐ 30m ☐ 50m

SCREEN

☒ 1 ☐ 2 ☐ 3 ☐ 4  
☐ 5 ☐ 6 ☐ 7 ☐ 8

MAPS

☐ Vortac & fixes  
☒ ASR rings  
☒ Airports  
☐ Interstates

PRECIPITATION LEVELS

☐ Off ☒ 1-6 ☐ 3-6 ☐ 5-6

WIND SHIFT:

☐ Off ☒ On

PRINT SCREEN:

☒ YES ☐ NO

STATUS: 2208

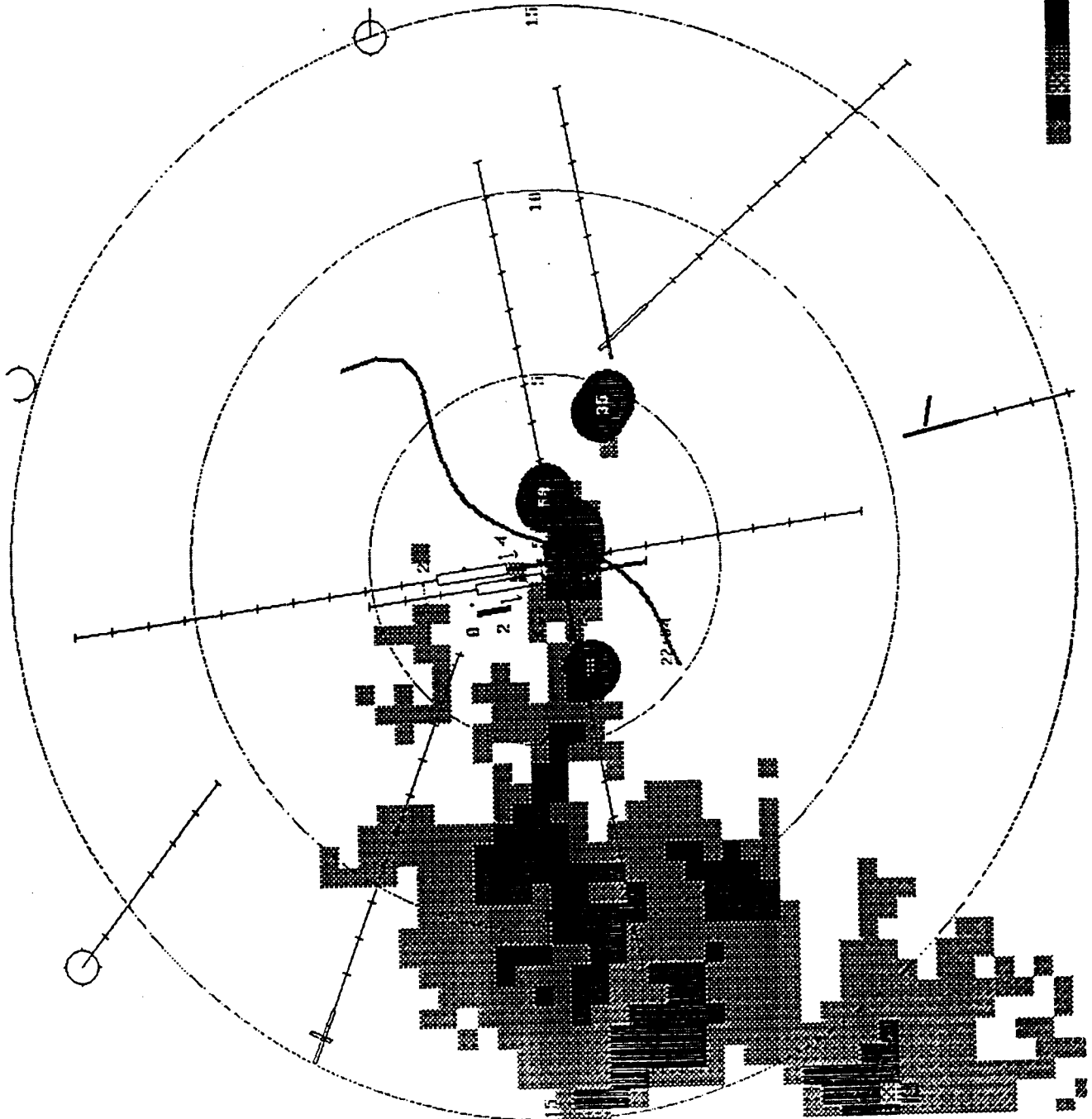
TIME: [REDACTED]

MB: UP

GF: UP

PRECIP: UP

LLWAS: UP





NCAR GSD

RANGE

5m 15m 30m 50m

SCREEN

1 2 3 4  
5 6 7 8

MAPS

☐ Vortac & fixes  
☒ ASR rings  
☒ Airports  
☐ Interstates

PRECIPITATION LEVELS

Off 1-6 3-6 5-6

WIND SHIFT:

Off On

PRINT SCREEN:

Print

STATUS: 2211

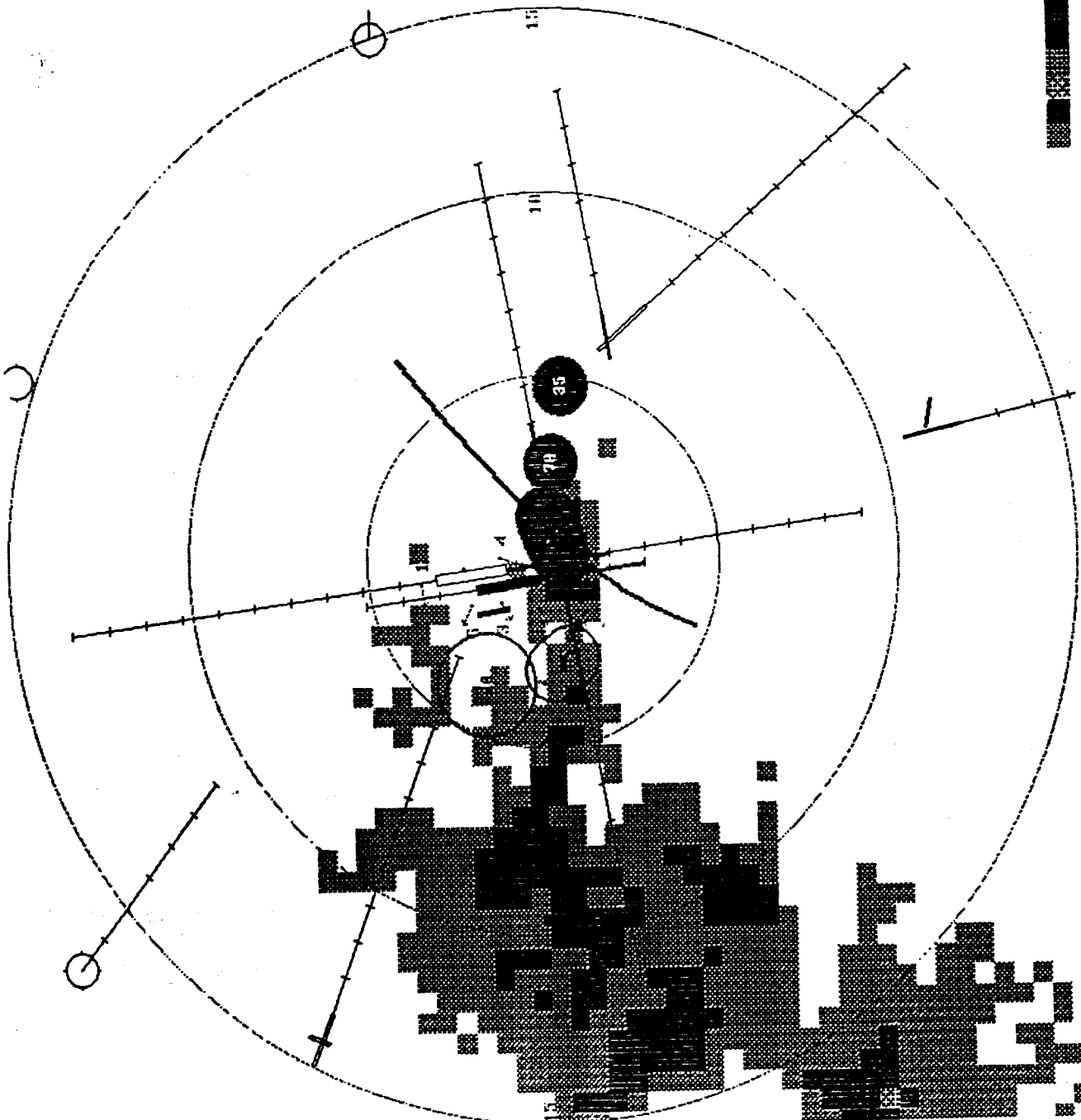
TIME:

MB: UP

GF: UP

PRECIP: UP

LLWAS: UP



NCAR GSD

RANGE

☒ 5m ☒ 15m ☒ 30m ☒ 50m

SCREEN

☒ 1 ☒ 2 ☒ 3 ☒ 4  
☒ 5 ☒ 6 ☒ 7 ☒ 8

MAPS

☐ Vortac & fixes  
☒ ASR rings  
☒ Airports  
☐ Interstates

PRECIPITATION LEVELS

☐ OFF ☒ 1-6 ☒ 3-6 ☒ 5-6

WIND SHIFT:

☐ OFF ☒ ON

PRINT SCREEN:

☒ YES ☐ NO

STATUS: 22/2

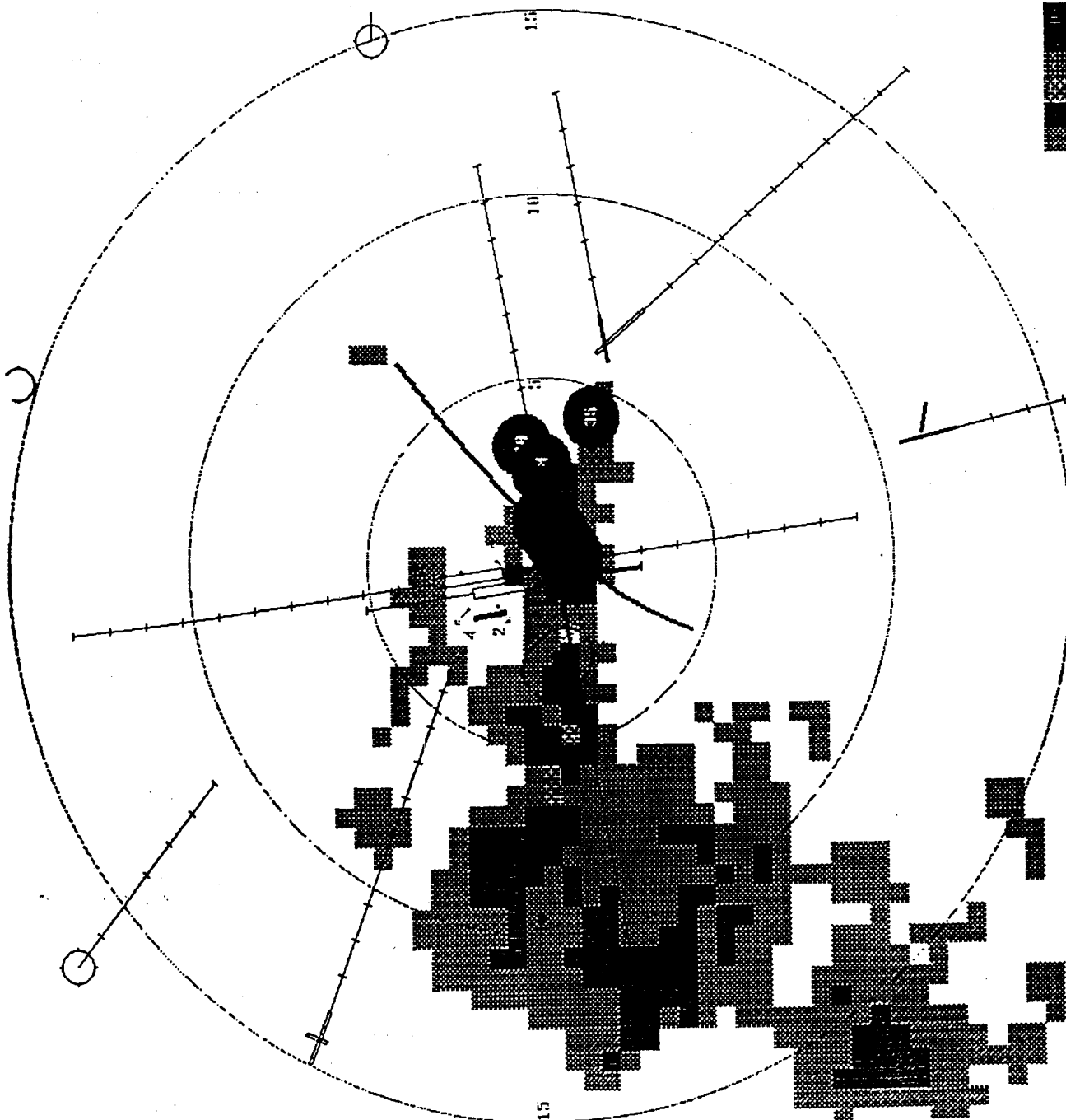
TIME: [REDACTED]

MB: UP

GF: UP

PRECIP: UP

LLWAS: UP



11 July 1988 Weather and

TDWR Alarm Summary

- \* This was a typical microburst day
- \* Microburst possibilities were forecast
- \* Sounding supported microburst potential
- Weak radar echos were present, about 35 dBZ at the start of the event
- \* Very light rain at the airport, dry microburst
- \* Extremely strong event, both  $\Delta V$  and divergence
- \* Event built rapidly, 0-80 kts in 6 minutes, normal for microbursts
- \* All pilots were aware of microburst potential
- \* All pilots were given microburst alarms
- \* Alphanumeric alarms contained all the pertinent data, TDWR successfully detected the event in a timely manner
- \* Geographic Situation Display very comprehensible and representative of complex data
- \* GSD primarily available to supervisors

## **Session II. Airborne-Hazard Definition**

Numerical Simulation of the Denver 11 July 1988 Microburst Storm  
Fred Proctor, MESO

**NUMERICAL SIMULATION OF THE  
DENVER  
11 JULY 1988  
MICROBURST STORM**

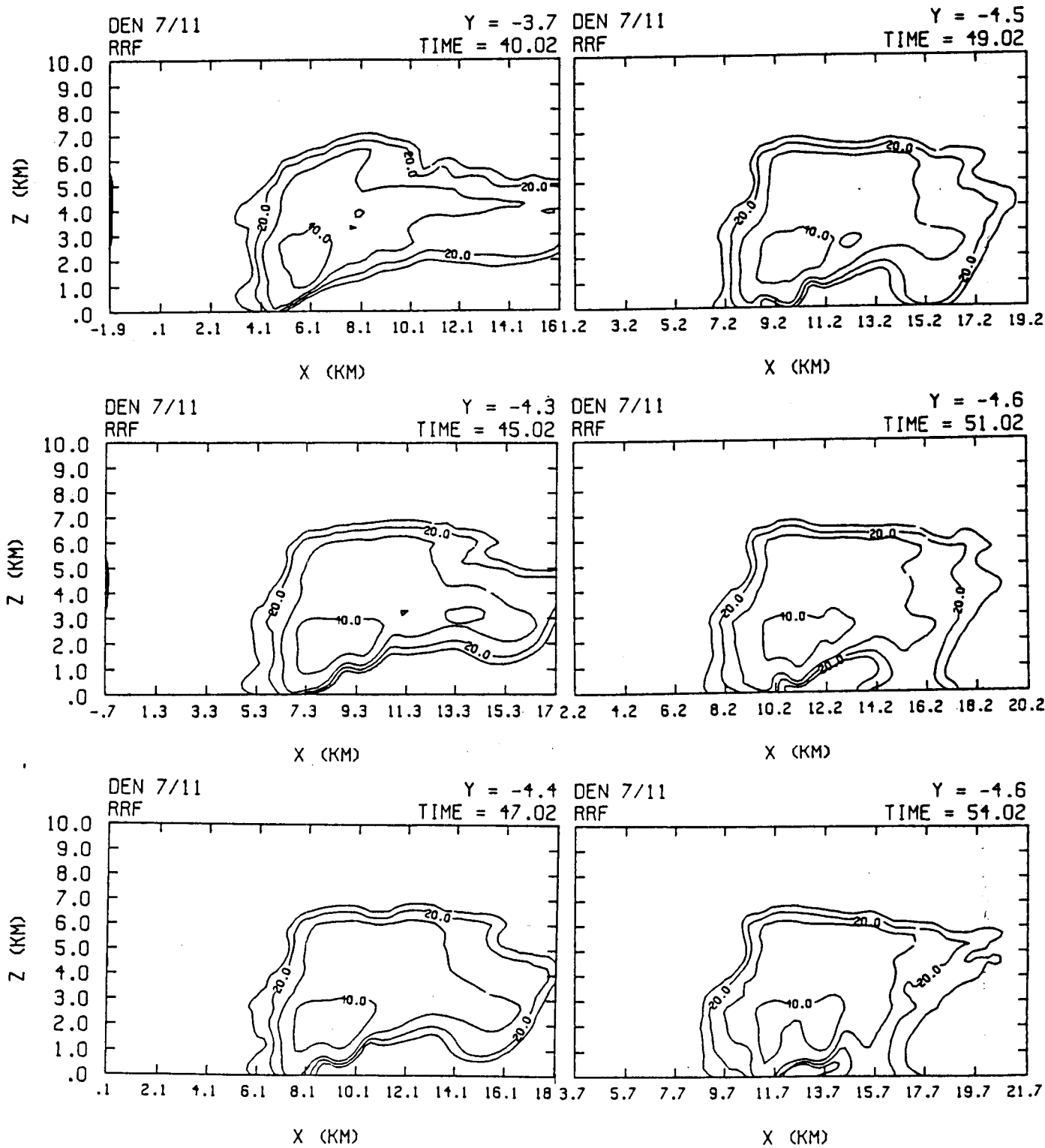
**FRED H. PROCTOR  
MESO, INC.  
HAMPTON, VA**

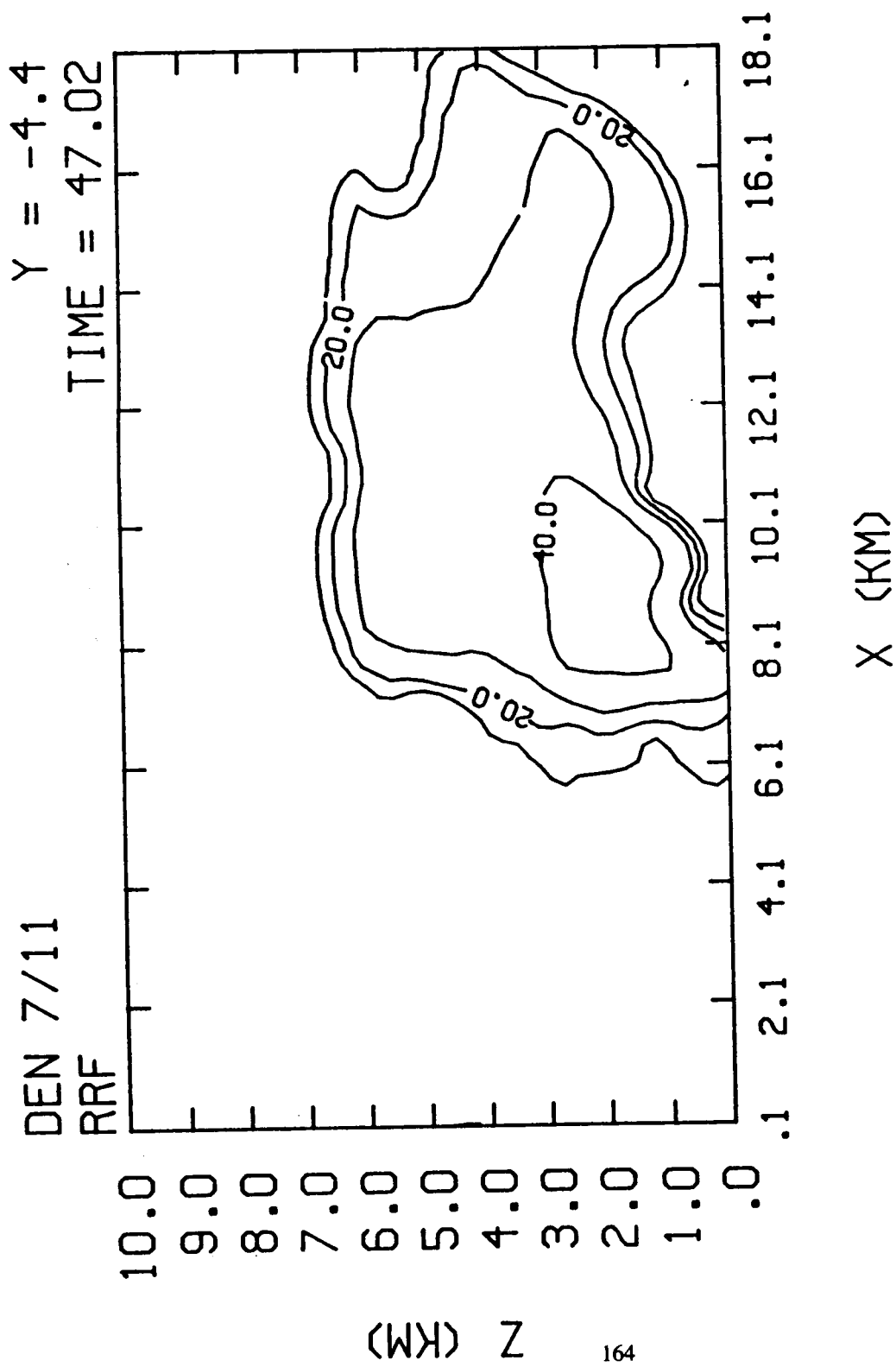
**NASA LANGLEY CONTRACTOR**

**DENVER 1 1 JULY 1988**

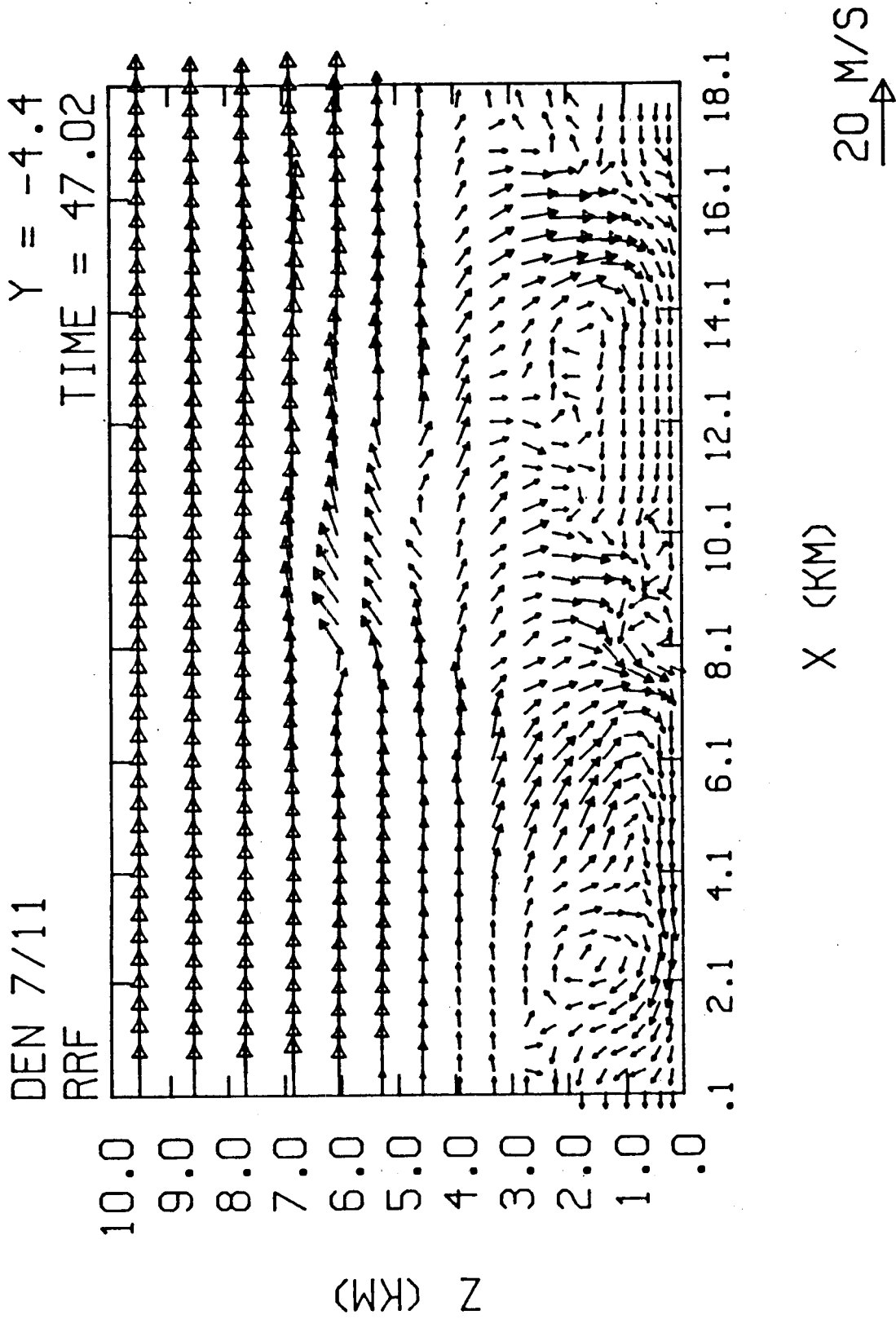
# **INPUT DATA / ASSUMPTIONS**

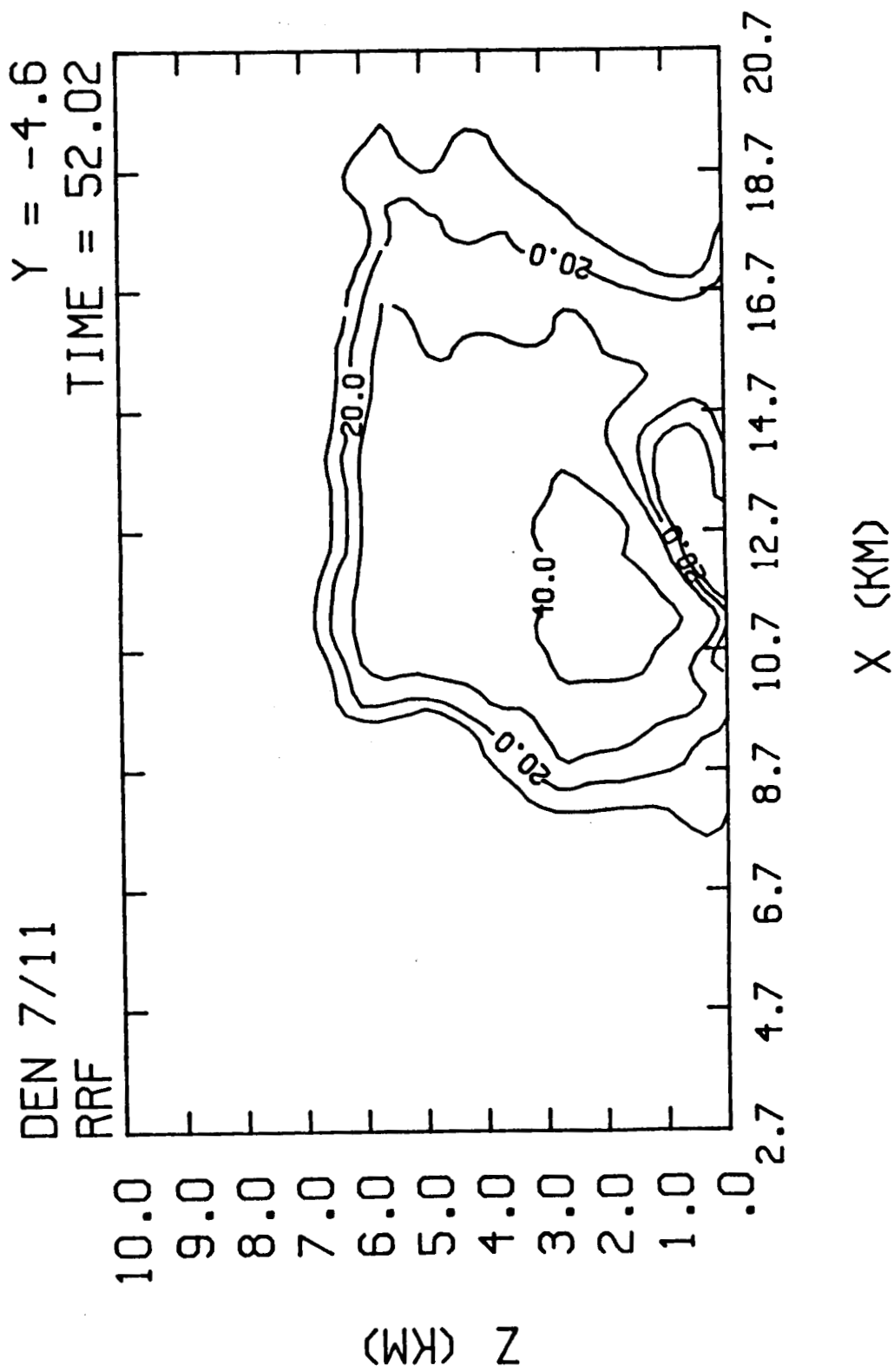
- **INITIAL CONDITIONS FROM OBSERVED DENVER SOUNDING AT 2000 GMT (MODIFIED FOR SURFACE TEMPERATURE AT 2200 GMT)**
- **PHYSICAL DOMAIN SIZE - 18 KM X 12 KM X 10 KM**
- **COMPUTATIONAL RESOLUTION**
- **HORIZONTAL - 200 M**
- **VERTICAL - 80 M NEAR THE GROUND TO 475 M AT 10 KM**
- **93 X 63 X 36 GRID POINTS**
- **CONVECTIVE INITIATION AT TIME ZERO**
- **SPEROIDAL THERMAL IMPULSE**
- **DIMENSION - 5 KM HORIZONTAL, 2.5 KM VERTICAL**
- **PEAK AMPLITUDE 1.5° C**

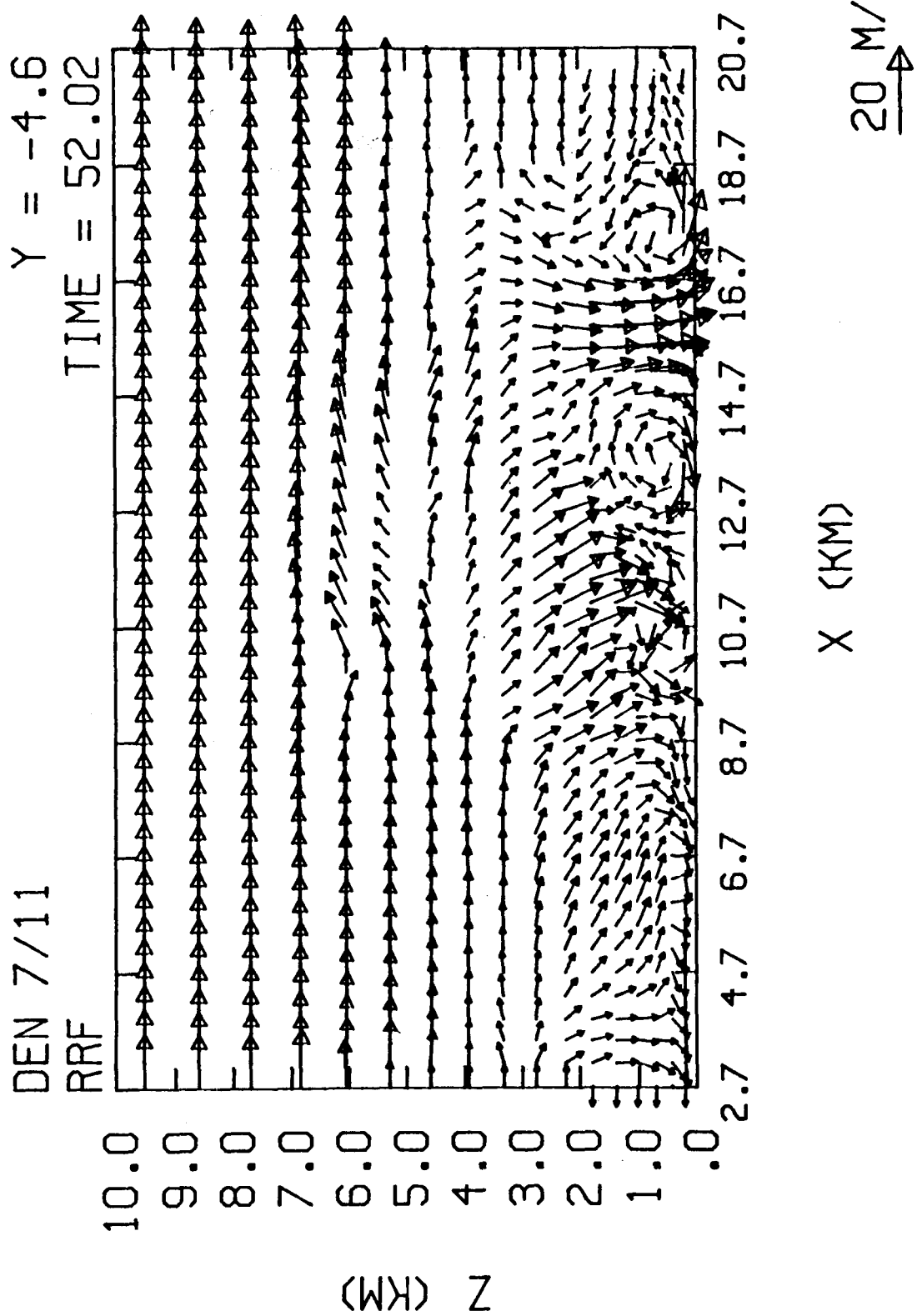








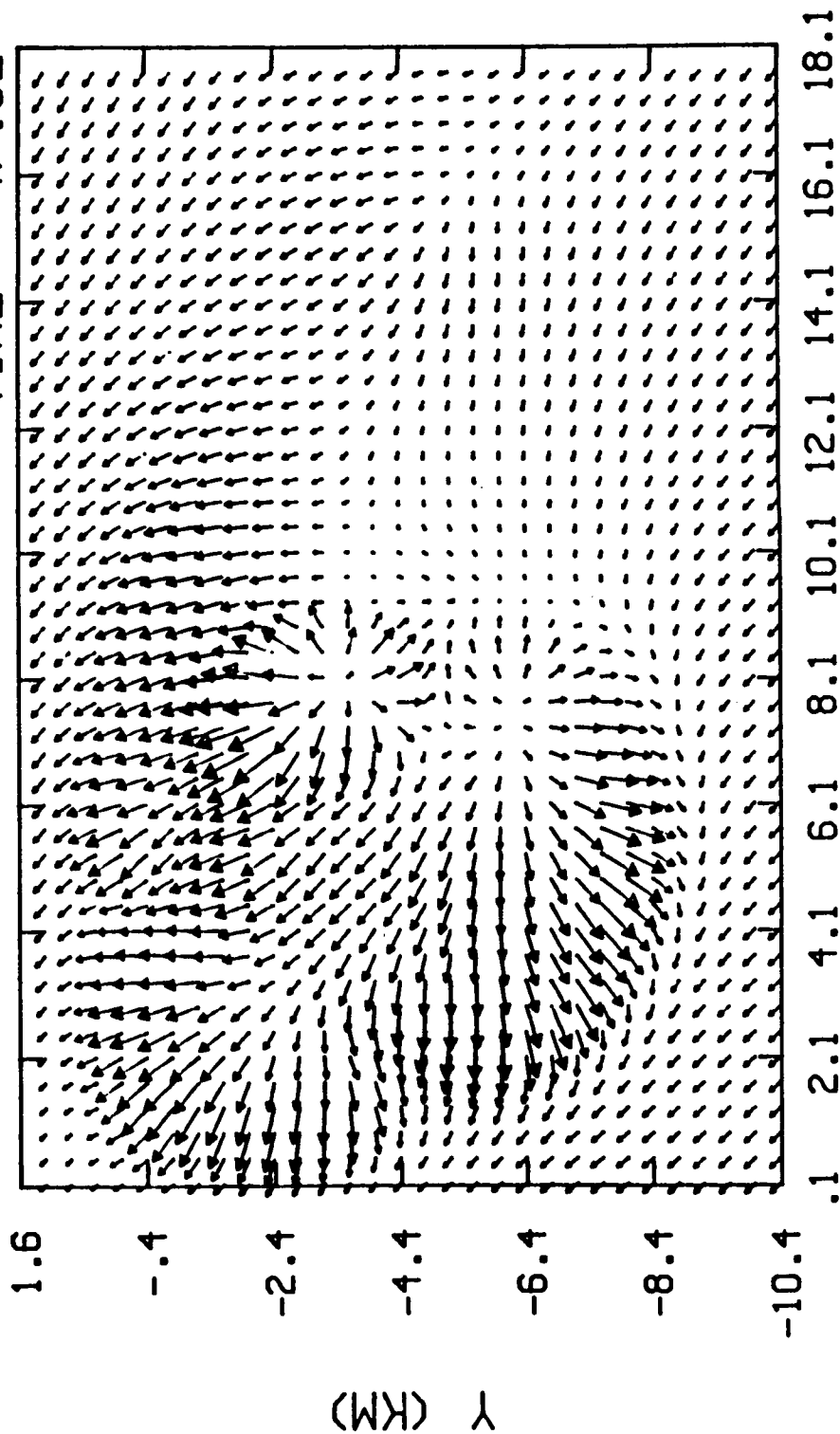




DEN 7/11

Z = .08

TIME = 47.02



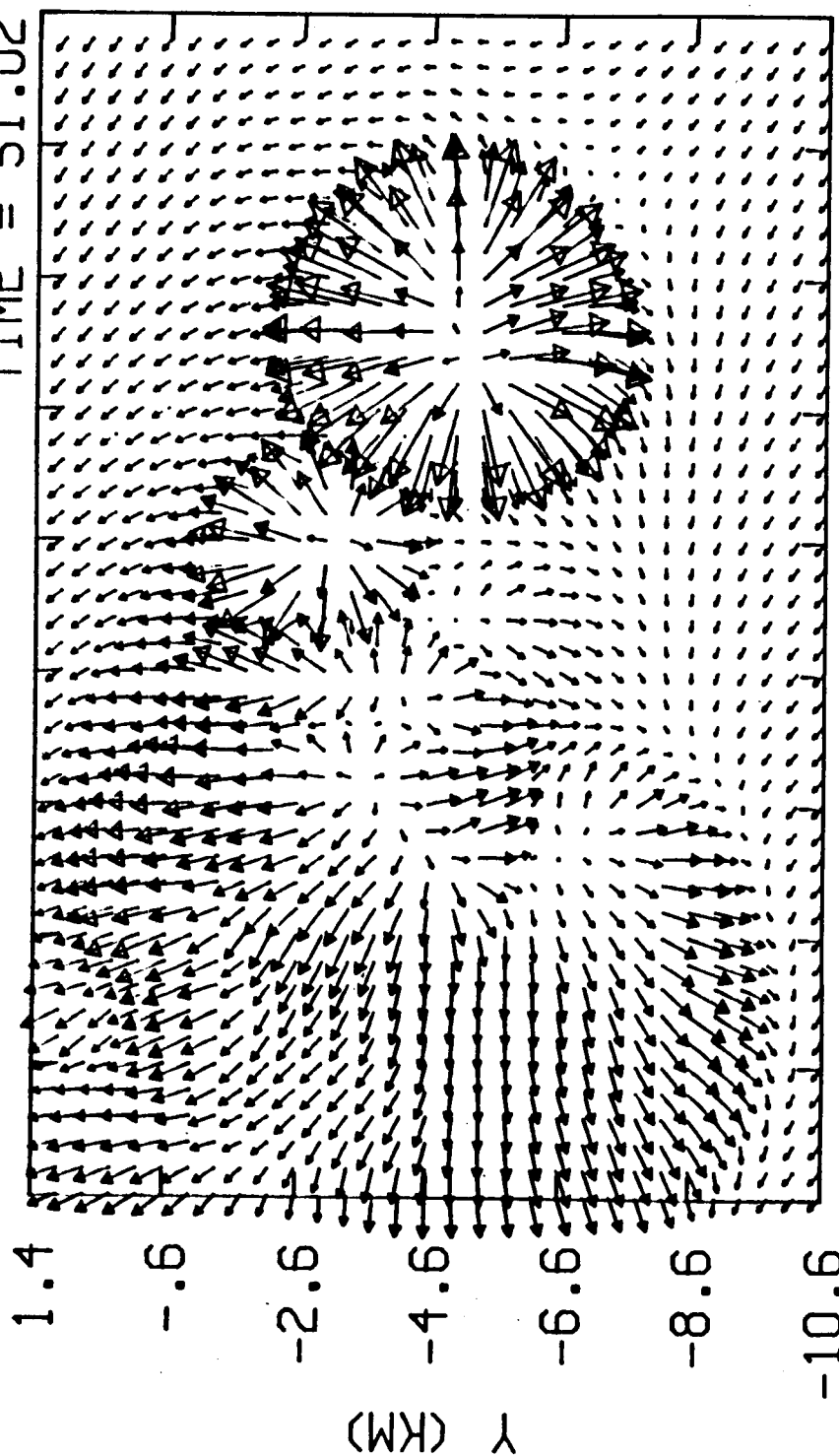
X (KM)

20 M/S

DEN 7/11

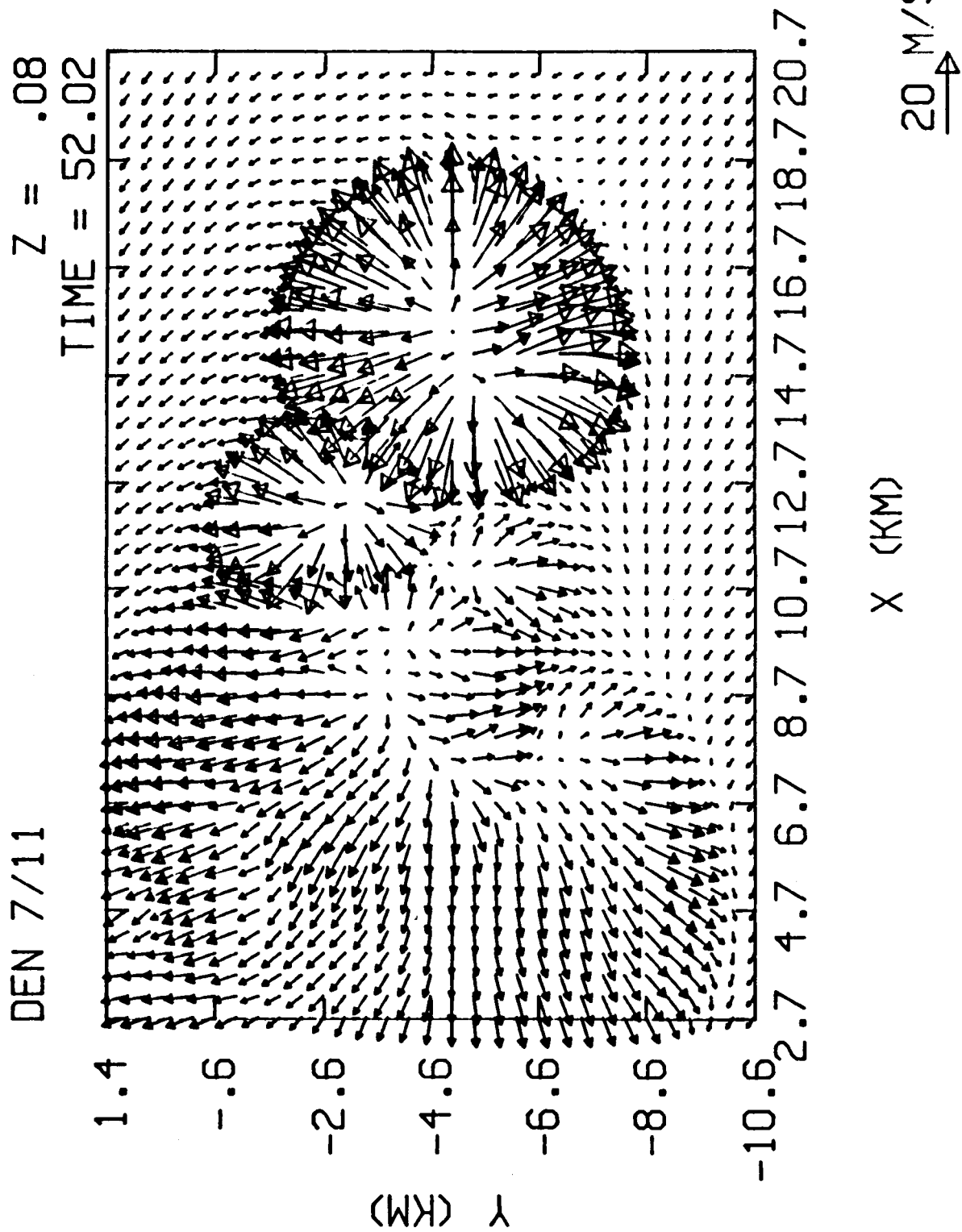
Z = .08

TIME = 51.02



X (KM)

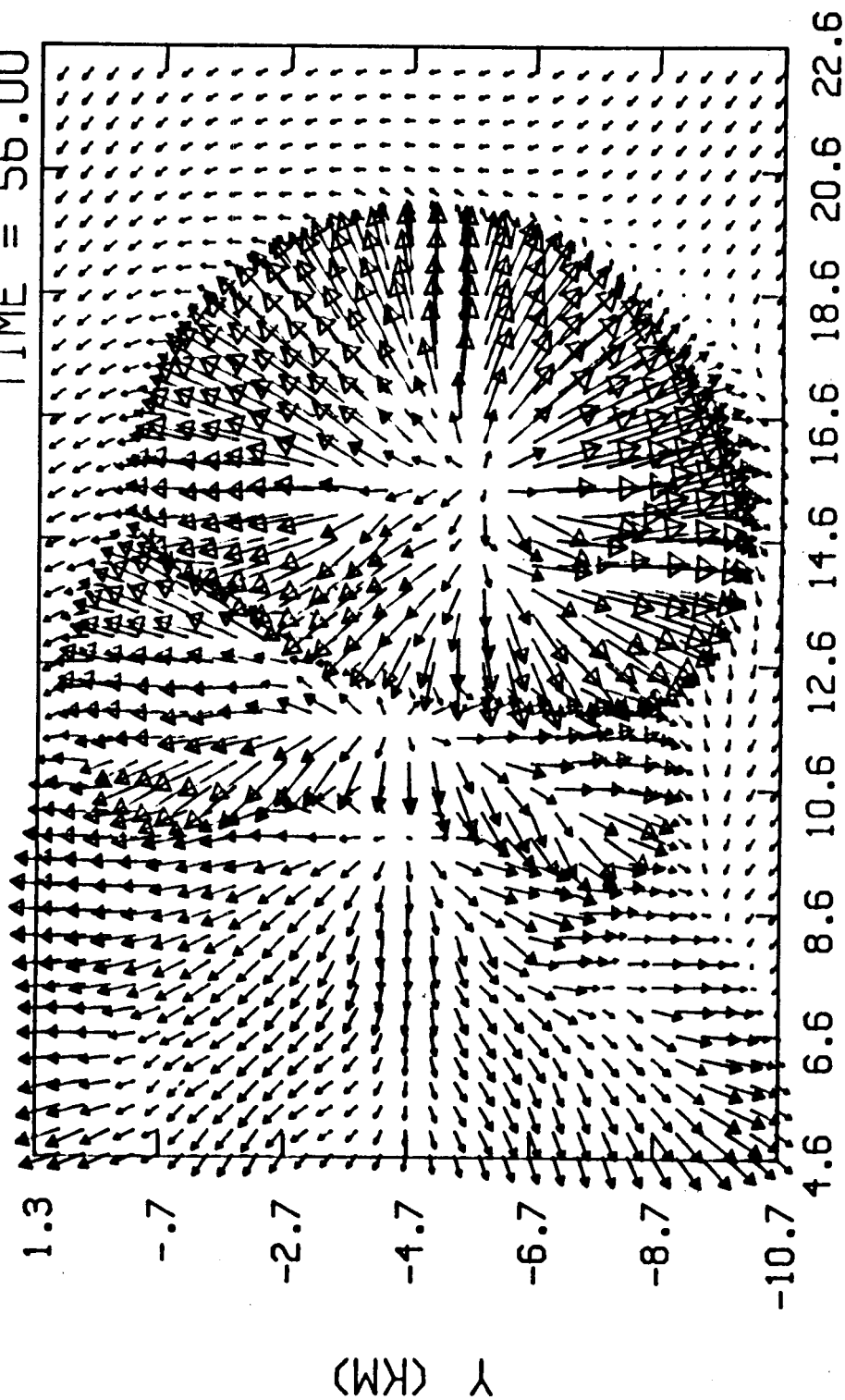
20 M/S



DEN 7/11

Z = .08

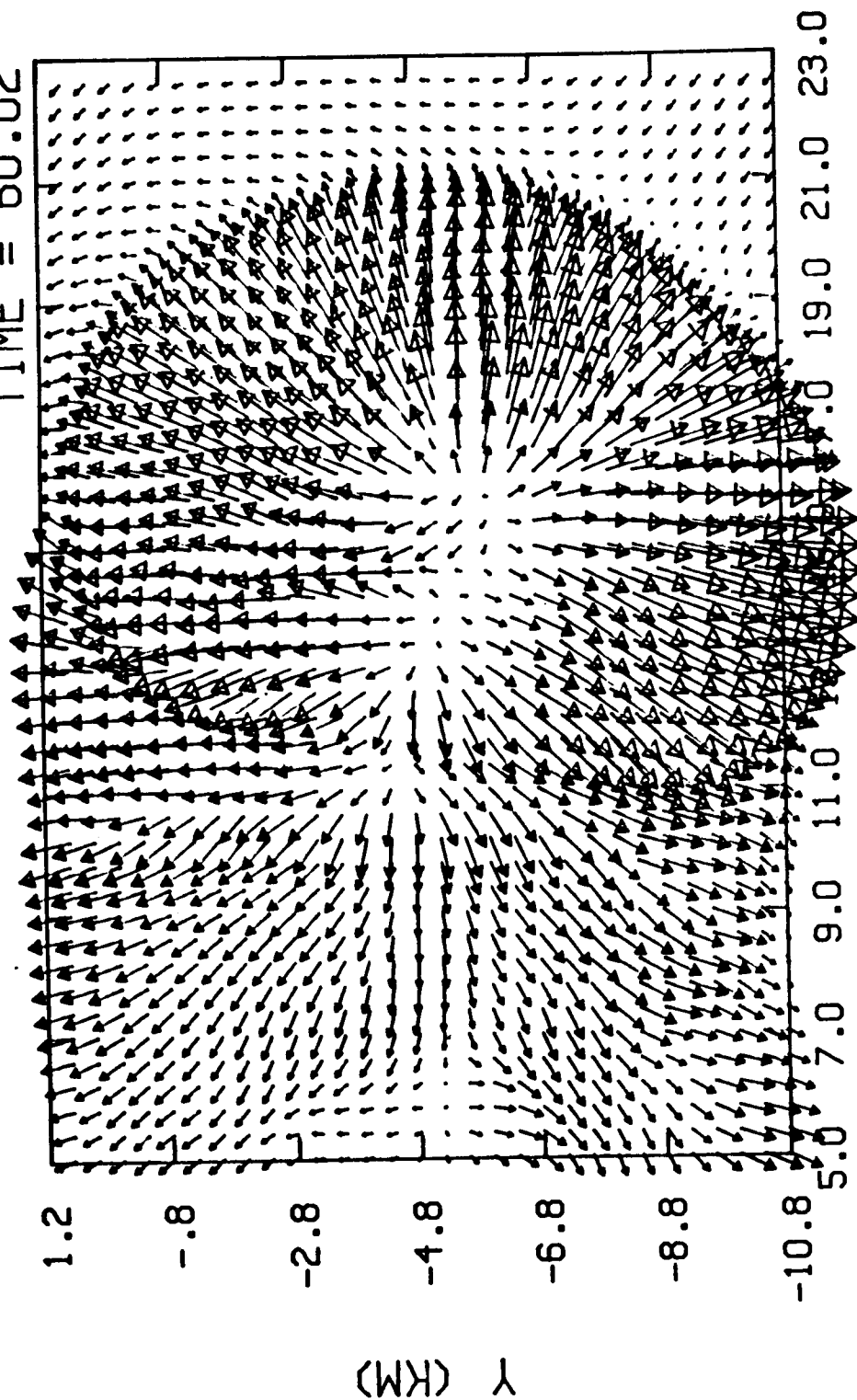
TIME = 56.00



X (KM)

20 M/S

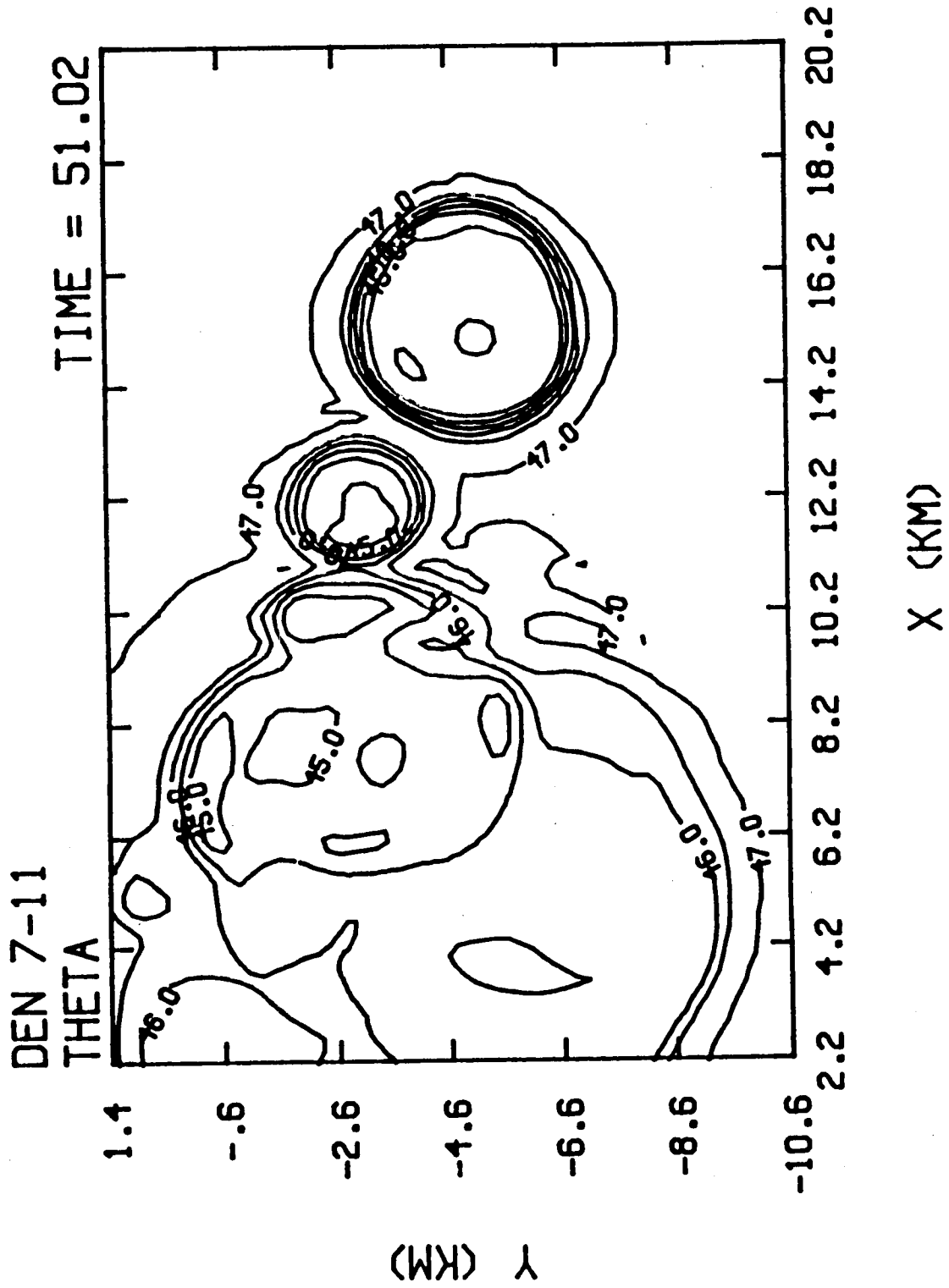
DEN 7/11  
Z = .08  
TIME = 60.02



X (KM)

20 M/S



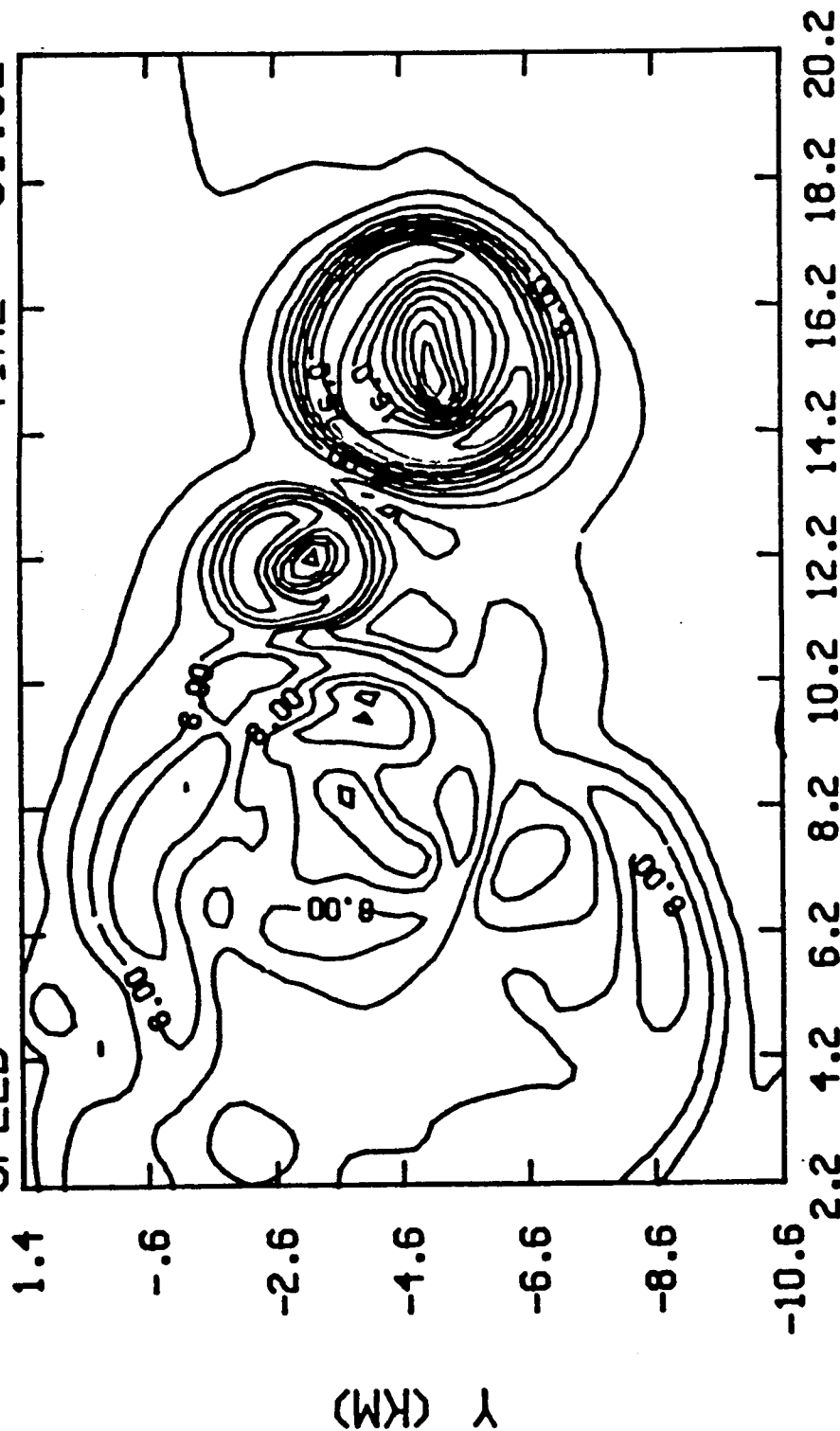


CONTOUR FROM 43.500 TO 47.000  
CONTOUR INTERVAL IS .50000

DEN 7-11

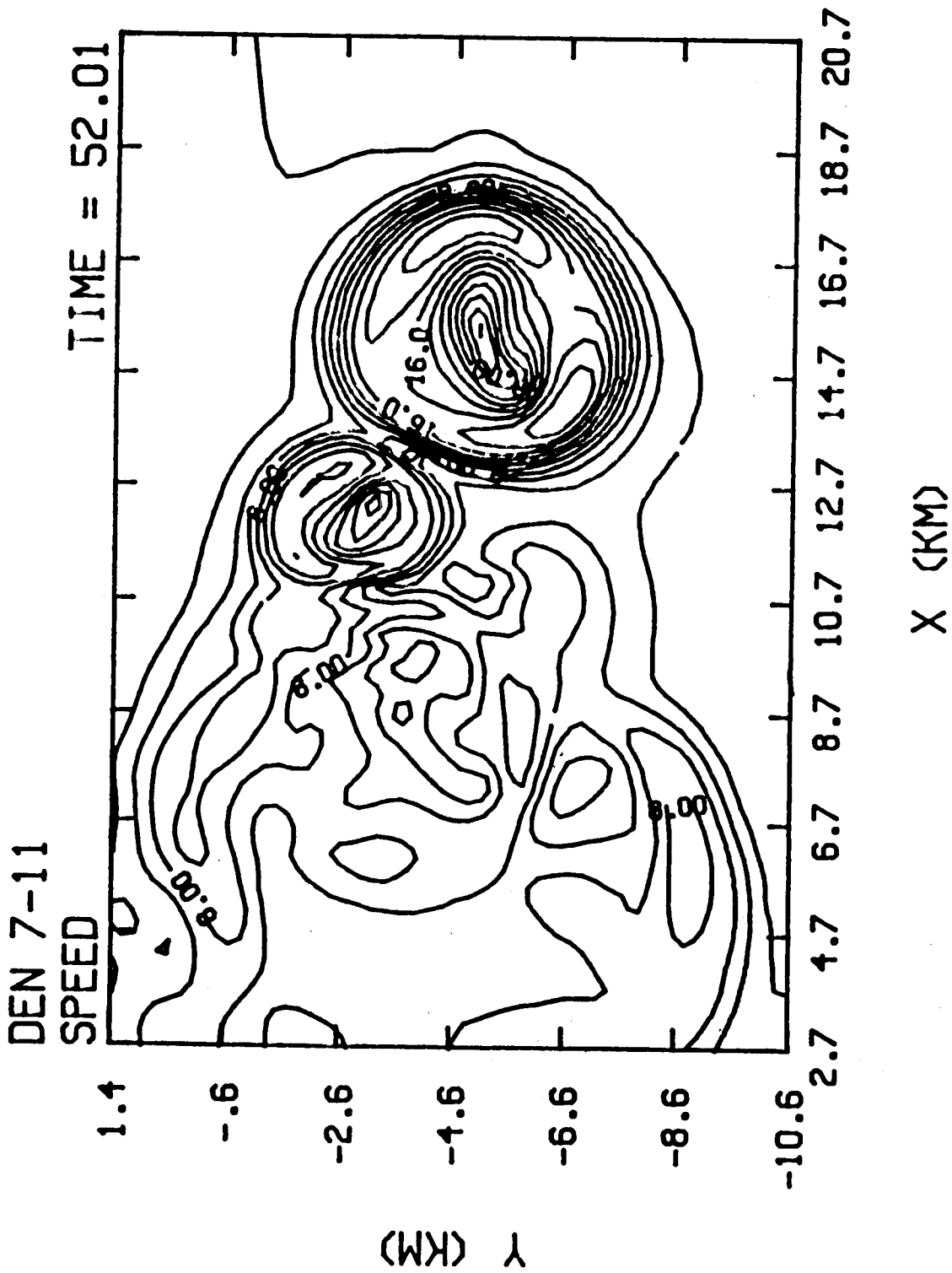
SPEED

TIME = 51.02



X (KM)

CONTOUR FROM 0.0000 TO 20.0000  
CONTOUR INTERVAL IS 2.0000

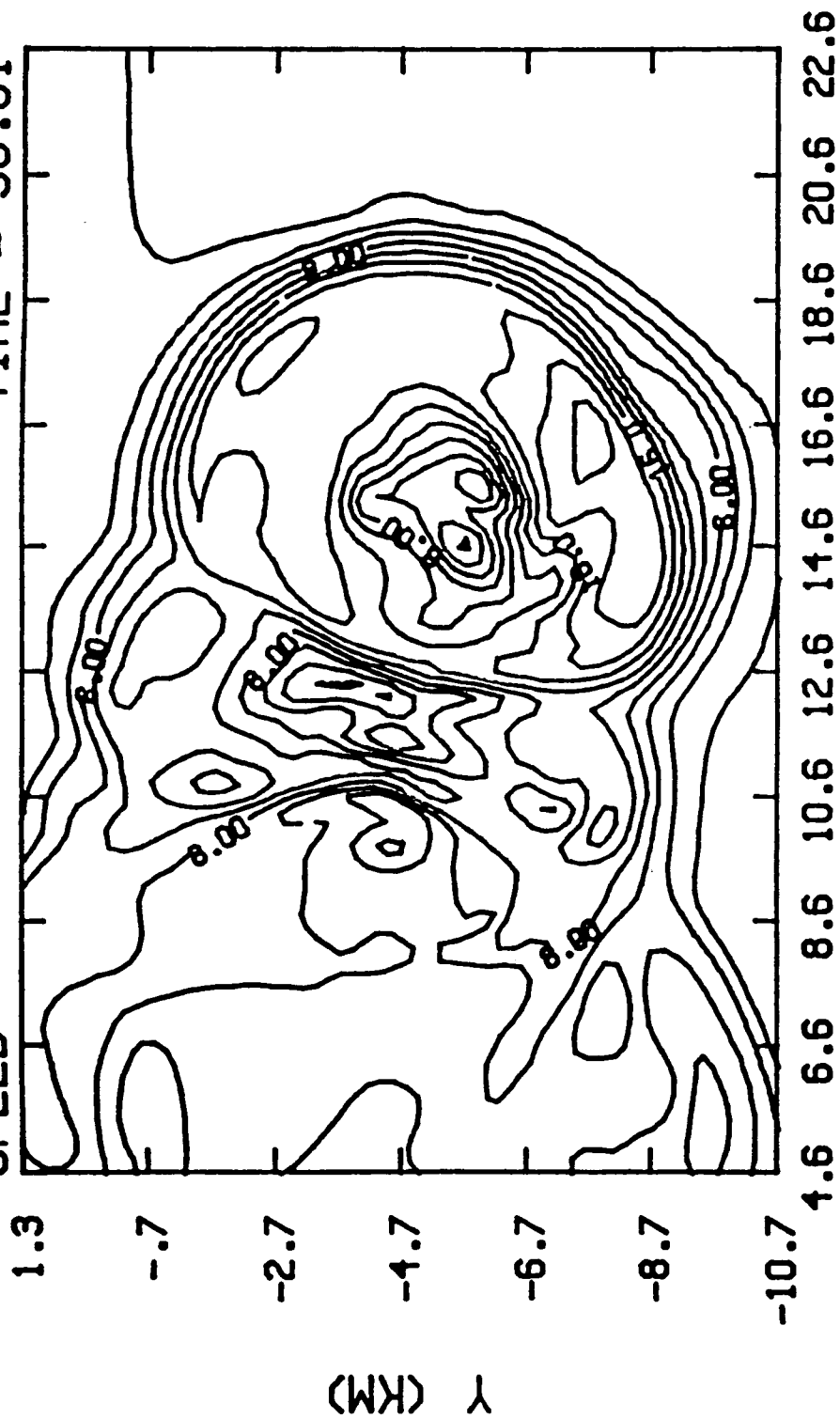


CONTOUR FROM 0.0000 TO 20.0000  
CONTOUR INTERVAL IS 2.0000

DEN 7-11

SPEED

TIME = 56.01



X (KM)

CONTOUR FROM 0.00 TO 20.000  
CONTOUR INTERVAL IS 2.0000

# **SUMMARY AND CONCLUSIONS**

- **MULTIPLE MICROBURSTS**
- **STRONGEST FROM ANVIL**
- **PEAK  $\Delta V$  - 40 MS<sup>-1</sup> / 3 KM**
- **LOW - PRECIPITATING STORM**
- **RAINFALL TOTALS LESS THAN 0.02 IN.**

## **Session II. Airborne-Hazard Definition**

11 July, Denver Wind Shear Encounters  
Robert L. Ireland, United Airlines

11 JULY 1988 DENVER WINDSHEAR ENCOUNTERS

527406  
N91-11688

Robert L. Ireland  
United Airlines, Inc.  
Denver, CO 80207

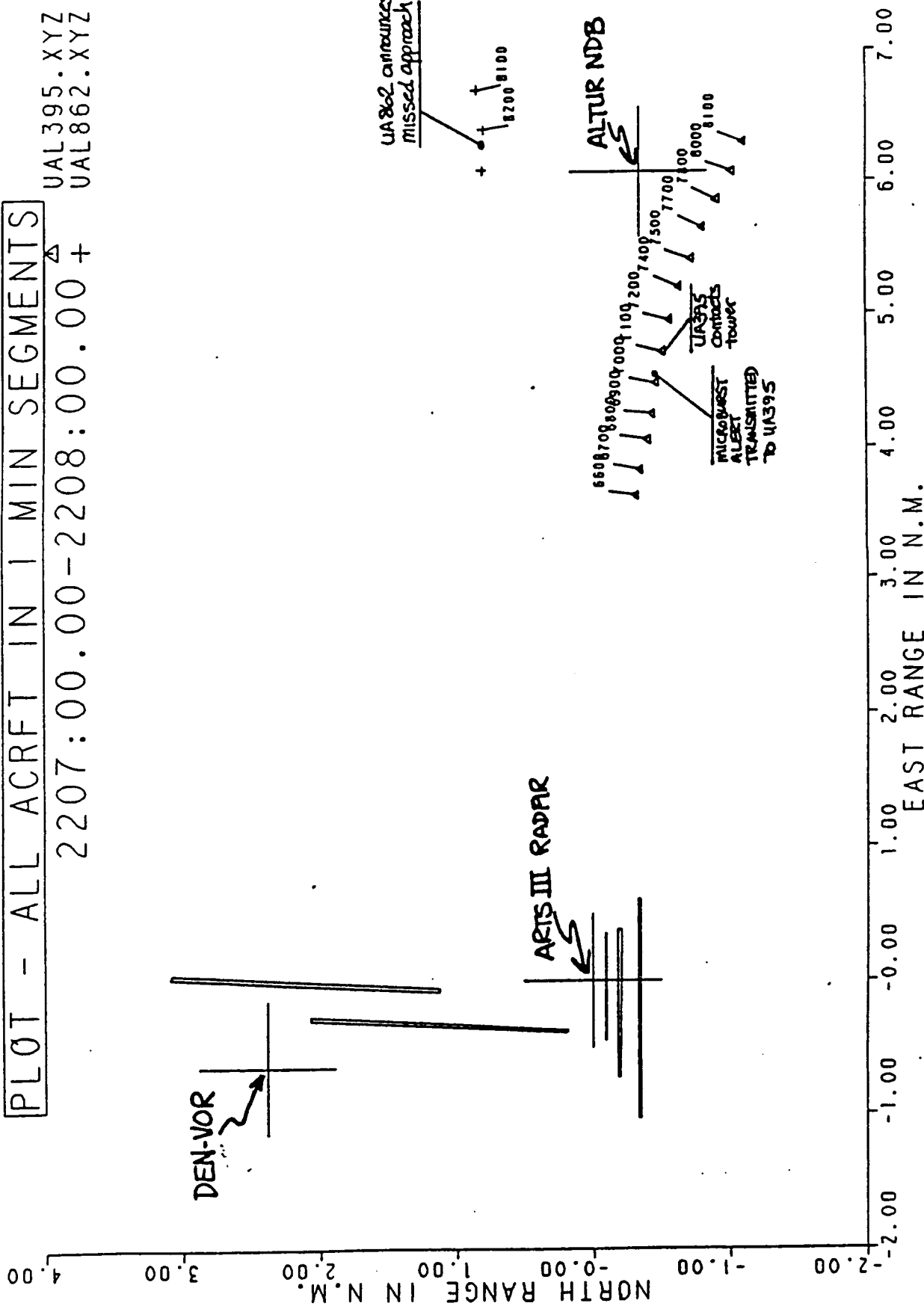
ABSTRACT

On July 11, 1988, between 2207 and 2213 UTC (16:07-16:13 MDT), four successive United flights had inadvertent encounters with microburst windshear conditions while on final approach to Denver Stapleton Airport (DEN), each resulting in a missed approach, subsequent delay, and uneventful arrival. A fifth flight executed a missed approach without encountering the phenomena. There was no damage to aircraft and no passenger injuries were incurred. The term "inadvertent" is used within United Airlines' windshear training materials and the FAA Windshear Training Aid to connote an encounter with windshear after vigilance and cautionary practices fail to identify and afford complete avoidance of the hazardous area. No crew culpability is implied. A comprehensive investigation for scientific purposes in the study of windshear phenomenon is being conducted separately under the guidance of the FAA with involvement and cooperation from United, NTSB, National Center for Atmospheric Research (NCAR), ALPA, APA, Boeing, Douglas, and NASA.

# PLOT - ALL ACRFT IN 1 MIN SEGMENTS

UAL395.XYZ  
 UAL862.XYZ

2207:00.00-2208:00.00 +

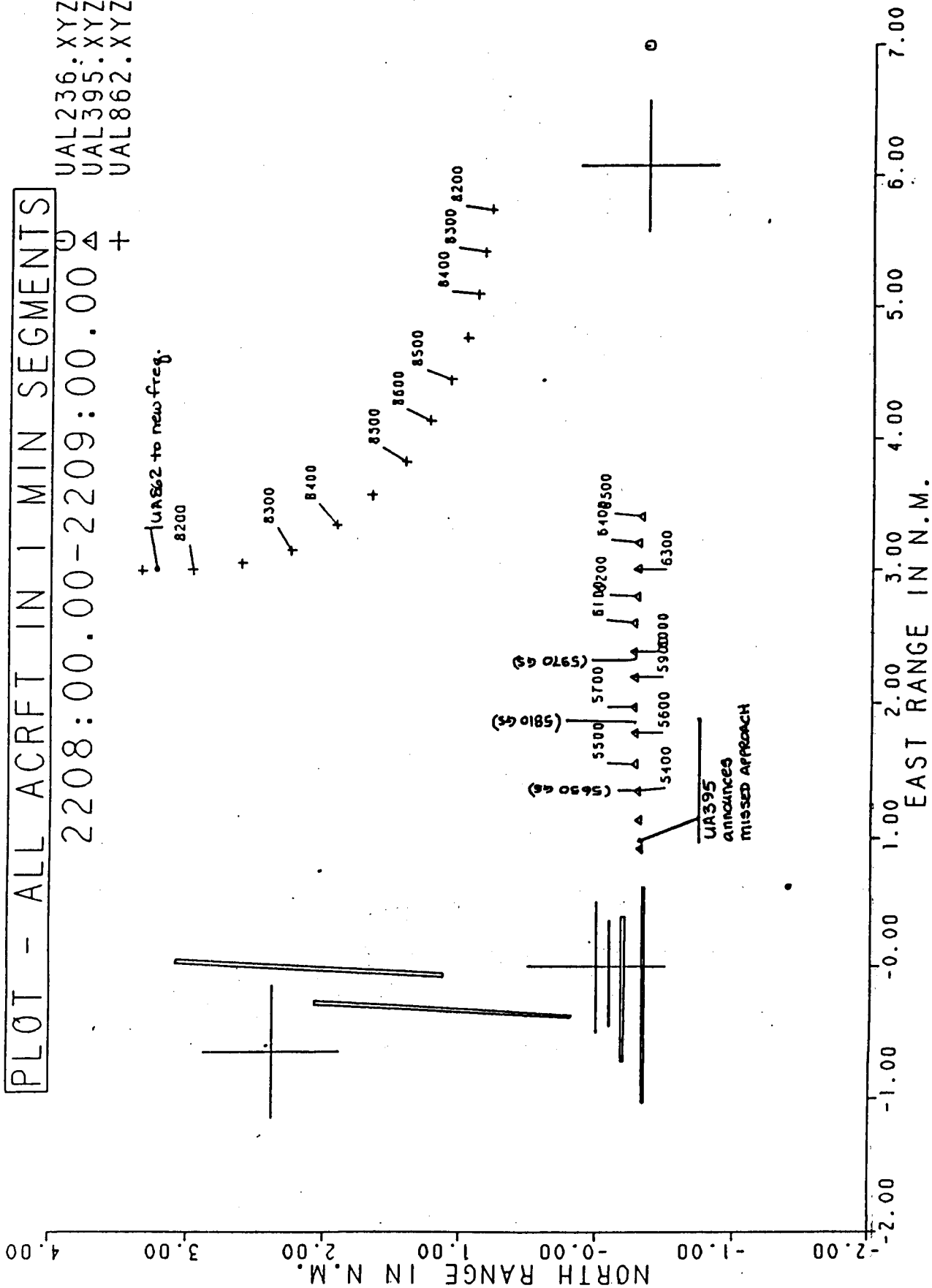




# PLOT - ALL ACRFT IN 1 MIN SEGMENTS

UAL236.XYZ  
 UAL395.XYZ  
 UAL862.XYZ

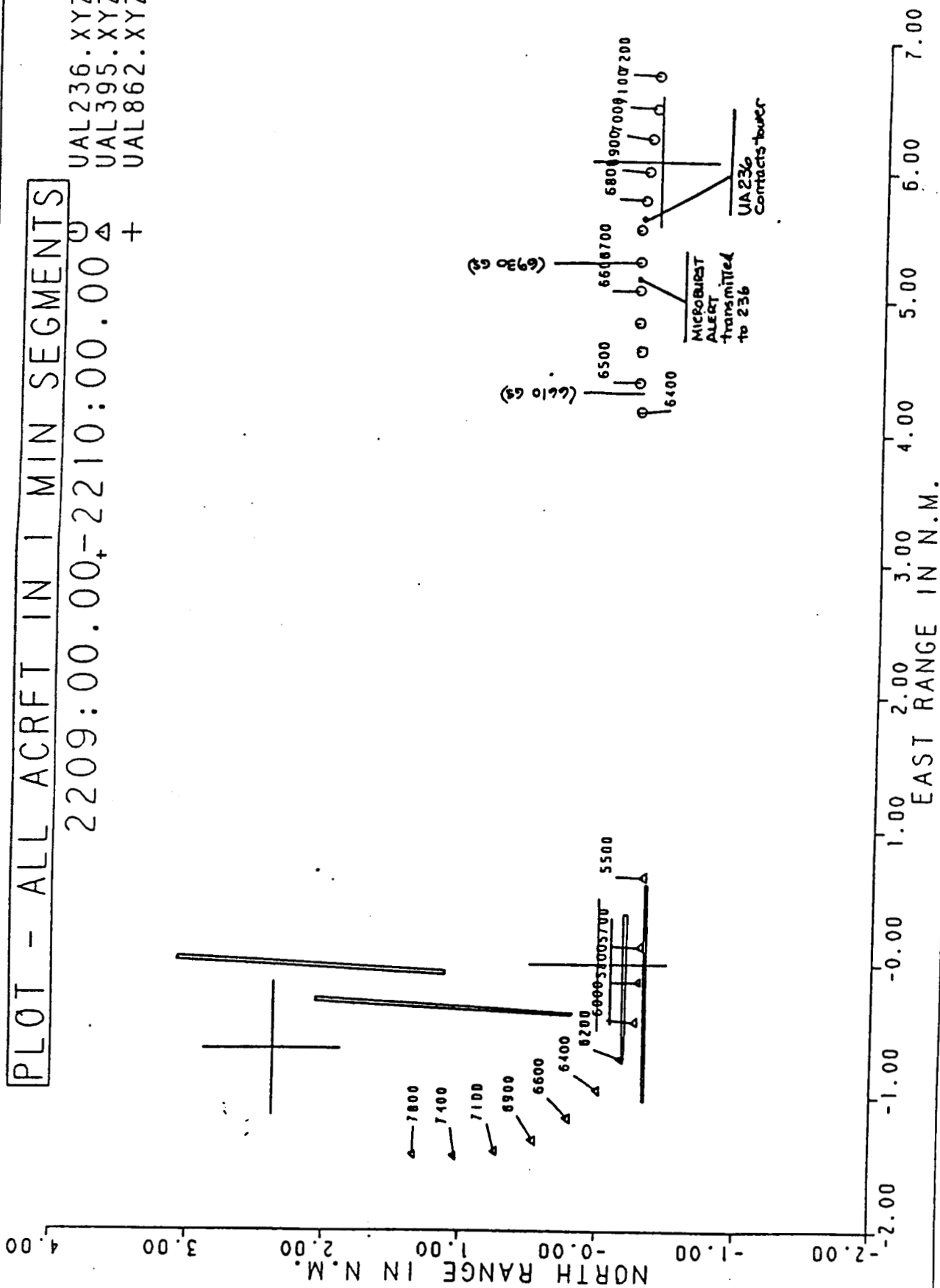
2208:00.00-2209:00.00



# PLOT - ALL ACRFT IN 1 MIN SEGMENTS

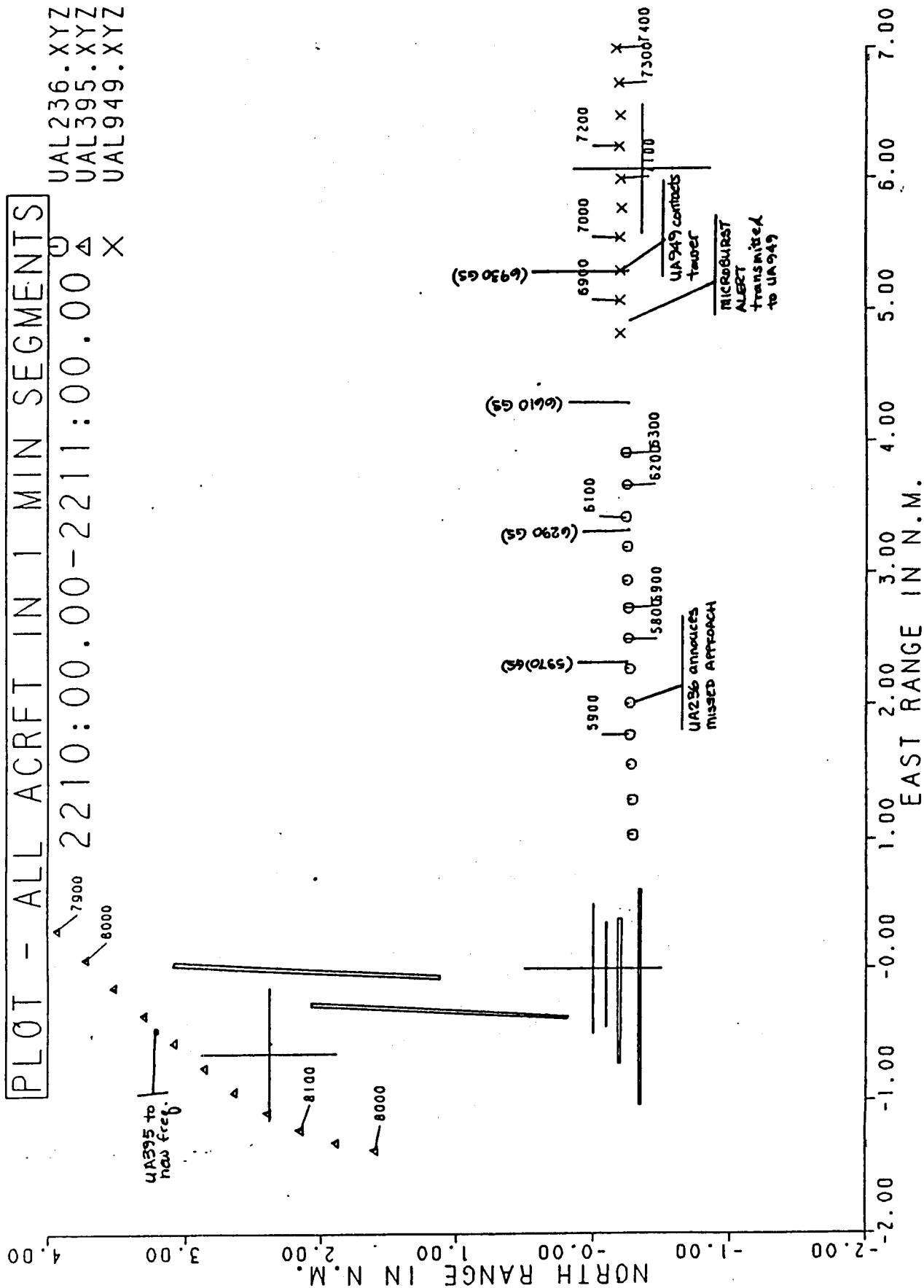
UAL236.XYZ  
UAL395.XYZ  
UAL862.XYZ

2209:00.00-2210:00.00 +



# PLOT - ALL ACRFT IN 1 MIN SEGMENTS

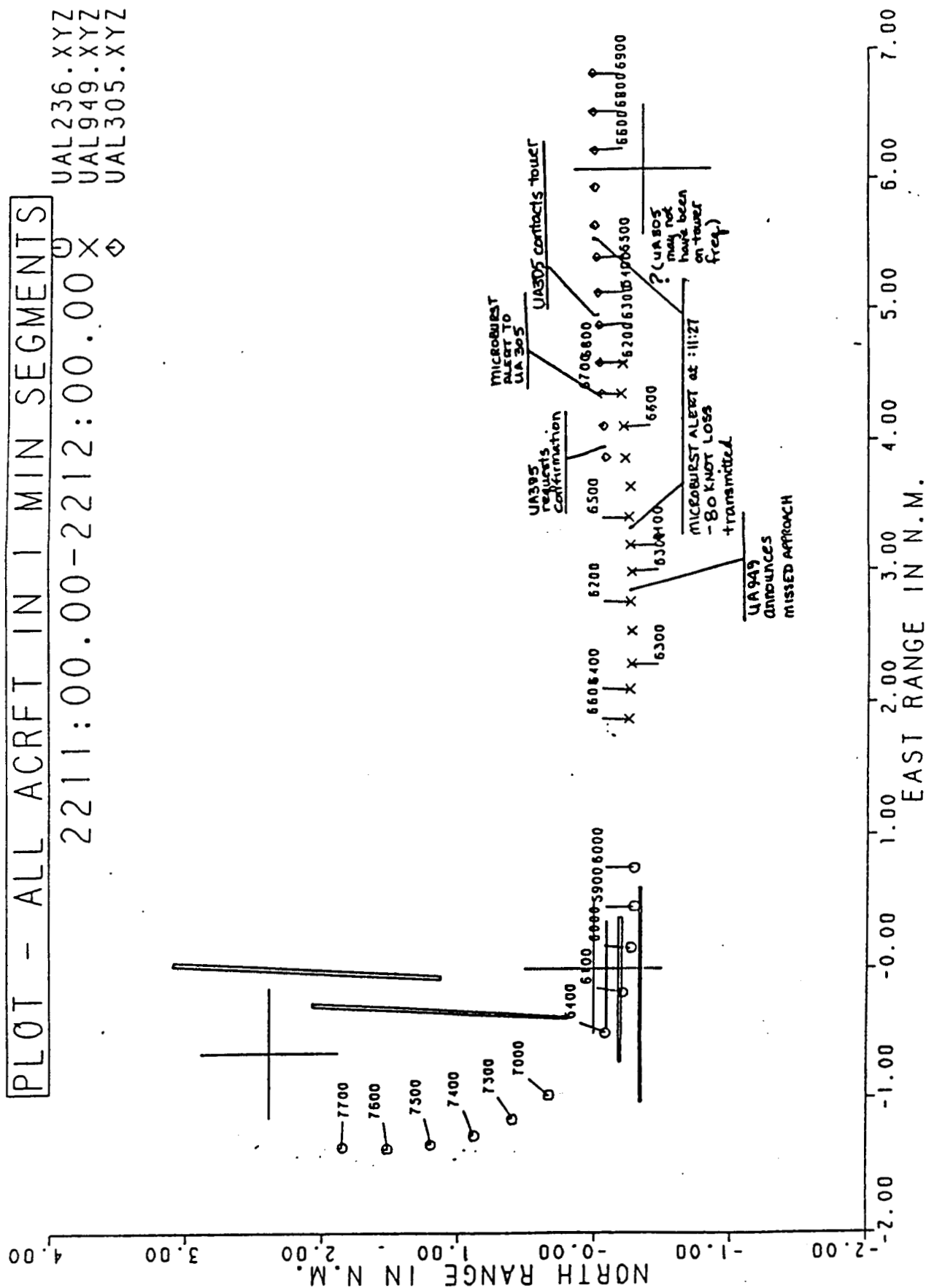
UAL236.XYZ  
 UAL395.XYZ  
 UAL949.XYZ



PLOT - ALL ACRFT IN 1 MIN SEGMENTS

UAL236.XYZ  
UAL949.XYZ  
UAL305.XYZ

2211:00.00-2212:00.00 X





## Questions and Answers for 18 October Sessions I and II

Questions and Answers 18 October 1988

Mark, a question or two. One nice thing about questions at least you know the people were awake when they listened to you. Mr. Biake, I hope I pronounced that correctly, just a point of clarification you state that Doppler or Lidar can only detect out flows. This is not correct. Lidar systems, unlike Doppler systems which make /?/011 clutter can be used in an up and down angle pointing mode to resolve the vertical wind velocity component. So, with that, we go to Rev. A. Vertical wind. That's what really what this was intending to do, was to promote discussion like that.

Second question from Howard Long at Delta. Q: Should the warning from TDWR systems be transmitted to the cockpit and displayed through on board reactive systems?

A: Currently, there is nothing defined to do that, capability exists in ACAR systems or possibly with TCAS COM CMCOM D, to do that type of work. You'd have to .. if you wanted to light the red light determine what magnitude, I guess of a detection that TDWR picked up to illuminate the red light. Maybe if we get into providing GSD type displays in the cockpit, this might be a subset of that, whereas the GSD, which is like the situational display would display the airport area and the events surrounding it, however, once it reached a certain magnitude, like the light in the cockpit, which would mandate a go around, that's a possibility. Does that answer your question? Anything else?

Earl Dunham, NASA LaRC.

I have seven question, some of them have more than one part to them and I looked these questions over and I said they're very good. There's a couple of them I wish

I knew the answer to. But let's start with them and go through them as they come up.

Question 1 - Wayne Sand and he asked the question, "How about some of the other questions addressed by Jim Loors, such as the weight of water and the physics of why CL is decreased, are these valid questions." Yes, they are valid questions as a way of background information, I'm sure you're aware of it because you used Mr. Loors name. About 8 years ago, NASA had a contract with Jim Loors at the University of Dayton Research Institute and once he did a little analysis that said that if he considers all of the physics that he can think about and how rain would interact with an airplane light, it increases the weight of the airplane because there's a water film on it. It increases the surface roughness which increases the skin friction on the airplane, changes the drag characteristics and he made his hypothesis that there were probably also some associated changes in lift performance. Well, his initial analysis is what started us down as an experimental program because we looked at what he did and says his argument are good, there may be something there, but there is no data available to us and so that's what was the genesis of what we're involved in right now, so yes, he did ask good questions.

Question 2 - Question by Joe Yasafi, What is the expected affect of the inplate on the test result, that is the drainage of the surface in water turbulence and what have you?

A: It turns out that we have run wind tunnel tests on complete wing configurations if you like, finite aspect ratio air pull, we've run wind tunnel tests with inplates on the air pull and the particular test that we're running on the large scale carriage, does have inplates on it. There's one of these difficulties that there's only a finite size structure you can place on this carriage and hope to run it down the track and not fly the carriage off of the track. The purpose of the inplate is to minimize the effects that we have by not using a full span wing. It's an attempt by channeling the flow



nice and straight down this little segment of wing that we have and basically, what you wind up doing is generating an effective larger aspect ratio wing. So, even though the wing span between those inplates is only about 14 feet, the wing cord is about 10 feet, it effectively in terms of aspect ratio, looks like it's a much bigger wing. The test criteria for doing this says we will have low wind conditions or we will attempt to make measurements in low wind conditions, I could share some of your concerns about the influence of water on the inplates itself. Most of these affects I think are going to be very near the end of the year for and not impact a major portion of the lift taking through the, say 80 or 90% of the span of this model that we have. It turns out, that what you would really like to have done was to put a 737 wing on top of this carriage and shoot it down. You get rid of all the problems of having to do this kind of modeling. Anyway I think it's a pretty good aerodynamic approach to the situation. Any more comments about it?

Question 3 - The question was asked about the mass flow of water coming down simulating rain, does it drag air with it and make a significant down flow velocity. It turns out that what we have tried to do in one little series of tests was to put an anemometer on the top of the spray rig and look at air being entrained as it came down and I hate to add, the anemometer didn't even spin as I recall. There was no measurable affect.

Question 4 - Jim Bull, Can you give the equivalence of rain water concentration, rain fall rate and millimeters an hour? For example, what did that number of 46 grams per cubic meter come out to in millimeters an hour? It's about 1,000 millimeters an hour. It turns out that the meteorologist do have an equivalency between liquid water content and expected rain fall rate. It's known as the Marshall-Palmer rain drop distribution that relates liquid water concentration to rainfall rate. It's fairly standard and accepted especially amongst the meteorology community and the radar community

because radars are somewhat calibrated against liquid water concentration. It's about this 46 grams per cubic meter. Now, there's a problem when I make that statement.

1) The Marshall Palmer rain drop distribution was developed in the 40's and it has since been tested and reevaluated but most of the time, that measurement is made for fairly low rainfall environments and it sort of gets extrapolated up to high liquid water concentrations such as this, but using that standard, you would get about 1,000 millimeters per hour. Is that really what you wanted to know?

Q: I'm Jim Bull and I'd like to add the question have any standards been set as far as what aircraft can operate in as far as rain fall rate. A: Well that's so to speak the final outcome of our program experiments and what have you. We don't know.

Q: Greg Solatola - MTSB. Earl, there's kind of a rule of thumb relating rainfall rate to liquid water content, approximately your rainfall rate in inches per hour equals your liquid water content. For instance, 4 inches per hour equals 4 grams per cubic meter. 40 inches per hour equal approximately 40 grams per cubic meter.

A: That's true following the Marshall Palmer distribution which is really developed the rainfall rate and liquid water concentrations down around the 1 to 2 inch per hour stuff. You just extrapolate it on up and say well it applies on up here when it's really hasn't been established that it does.

You ought to point out the difference between rates averaged over time as opposed to instantaneous rates. You might relate that little effort, that storm that came through the peninsula where you had your load cells operating.

Ok, well, it gets us involved in another issue of the probability of occurrence of a given rain fall rate of occurring and exactly what are world record rain fall rates, the established world record is like 79 inches an hour. It's an enormous rain fall rate and the statement that I usually make is you don't expect that to last very long and it didn't last very long. What you concern yourself with for our stuff and for the aerodynamics is the concentration of liquid water and the air mass that we're flying through. Now, there is a relationship that you can relate that to rain fall rate but, I'm talking about a concentrated region in a storm where there might be divergence of water so that the water gets concentrated in one spot. It may not deposit that particular concentration on the ground. We have measured during a thunderstorm, rain fall rates in the neighborhood of 17-18 inches an hour, but that's not what's accumulated on the ground because that only occurred over about a 15 - 20 second increment. As a matter of fact, it got measured by the same calibration technique that I showed earlier, not the coffee can, which I found out was sweet potato cans, I don't know how we got them, or where they came from, but anyway, it was measured with the little box that's just time derivative of accumulation of water.

Norm Gable - Aerospace Consultants - Q: Earl, what are your drop size distributions look like and how do they compare with natural rain? A: Ok, what do you want to talk, wind tunnel or this thing? The car wash. Alright, the car wash. We are in the process of measuring those drop size distributions. We have done some photographic measurements of them and they basically look like natural rain at that rain fall rate. We've got large drops on them following the same sort of distribution. We got at least two more.

Greg Solatela - Q: Following the Southern 242 accident at New Hogue, Georgia in the late 70's, the NTSB recommended that the affects of rain on weather radar ray domes be determined. Has this been done?

A: Well, what we did was we stuck a ray dome in the wind tunnel, and we measured .. let me backtrack a little bit, the questions relates to is there enough of a water film and mass of water on a ray dome since that the weather radar doesn't really penetrate out and see the hazards that are in front of it. With this particular accident, I think that they are suggesting that maybe the pilot didn't see how severe the weather was a mile or so ahead of them because he had such intense water on the ray dome. OK, what we did do at NASA LaRC was to do a small experiment in which we took a ray dome, placed it in the wind tunnel in that spray environment that we did tests on wings, aerodynamic testing on wings, tried to measure the water film thickness on that ray dome and that very intense rainfall rate. Well, the test was somewhat inconclusive, the results indicated some very small water film thickness. There was some discussion about the size of the water drops that we were using, even though we had the right concentration of water, whether it really would have sheeted up on the ray dome in the proper fashion because we didn't have the right size drops, because we used the full scale ray dome on them. We used the ray dome off of a T39 I think it was. So there were some questions about the way we scaled those tests in that result and then we saw some things in the testing that would lead us to believe that there's .. the rain drops as they hit the ray dome splatter back out and there's a certain mass of them that come up and get swept back in the boundary there and there's sort of a fog layer standing off of the ray dome and the question was asked how does the radar propagate through that because it's obviously had a very high concentration of water and even though the water film on the ray dome was small. We had decided at that time that what we really needed to do was a better job of scaling rain and the way

we're doing it is with an outdoor facility, and downstream in our test program is putting some sort of a ray dome on this test sled, doing some sort of a test that's not clearly defined yet but it hasn't been dropped and it is still being worked.

I've got four of them from Greg Ifel from Boeing - some of these are the easy ones.

Q: How is speed measured on the sled? A: Well that one's pretty easy, all of our data are TM backed to a control room and part of the TM is just speed right off the carriages, just a tick every ten feet down the track. Just a magnetic pickup and every ten feet down the track there's a little piece of metal and it's ticking it off, coming back with a function of time and that gives you velocity.

Q: Is local area ambient wind measured and considered?

A: And of course it is because we really want to get back from basic force measurements to aerodynamic lift and drag coefficients measurements, so we're operating in an environment in which the wind is blowing so we do have to consider that. It does get cranked in to it, whenever we calculate the lift coefficient. For lots of reasons we said we want to do most of our testing at low wind conditions, pointly because of variability in wind, even if you take it into account. You'd have to measure all the way down the track on the carriage.

Q: Am I checking the effect on air speed and angle of attack measuring systems. A: We did a series of tests, actually, Jim Lewis at University of Dayton Research Institute, did a series of tests in a little wind tunnel type facility that he had. There's a report available on what he did in the use of standard .. there's two types of angle of attack sensors in the industry. There's a little turbo driven pressure nulling and there's the flow vein. He used the flow vein, didn't look at the pressure nulling device but on the

flow vein, he saw very little effects and angle of attack. Most of the operational air speed heads that you use are set up for water drainage and seem to have little effect on those.

Q: Since the sled starts at 0 air speed with the wing at a fixed angle of attack, how are aerodynamics hysteresis to be accounted for?

A: I would like to talk to you a little bit more about that particular question. I'm not so sure I really fully understand it. My impression was that for this type of air flow, the hysteresis is very small, really only near CL mac and we probably wouldn't see it in the type of testing that we're doing. I'm aware of some work that was done by Dr. Jim Marchman at DTI, when he was looking at the hysteresis effect in and out of rain on an air flow, but he was looking at a laminar air flow, which has a pretty large aerodynamics hysteresis in it. I wasn't aware with a leading edge slap, pretty turbulent flow air foil that I would need to consider that type but maybe you and I ought to talk about that a little bit later.

Q: If you'll consider the problem analogous to say the gust, indicial gust response, who was the guy that asked the question, if you consider the problem similar to that of a indicial response of an air foil that is starting out at 0 angle of attack, you look at the classic solutions by cord lengths. You're practically up 90 percent of steady state. You go to 10 cord lengths, you know it is very close to steady state. So how many cord of lengths do you run before you hit the rain, Earl? A: 40 or 50. Q: Now, how long is your run through the shower? A: It's 500 ft. Q: So there are a considerable number of cord lengths elapsed. It's not an exact answer because nobody really knows what the hysteresis is on this thing, but we talked about this and thought about this in designing this system and by very crude analogy, it's 10 times bigger than in the drive case, so it should be very close to steady state. It's the best we can do.

Yea but ... I need to talk to you because I thought about that too Norman, in light of the transient analysis that we had done and looked at and also we've done some wind tunnel tests where we instantaneously turned the rain on, we instantaneously turned it off, looked at that. That's a time dependent characteristic. Hysteresis is not necessarily a time dependant phenomena. It's going to a state coming back and the path you took back. So I am aware of it for laminar flow air foil but one way after this, and I don't think really it's a problem, but you and I, I think should talk about this a little bit.

Don McClear, Boeing - Q: (tape difficulty) ....under a fixed angle of attack, an equilibrium lift for example, shoot in the ride. A: I have no difficulty with the transient effect. I think we've got enough run down the track, wet versus dry and what we've seen in the data, we do have the steady state value. There's no problem with that. That hysteresis one is .. As I understand it, the second question you're asking is if you change the angle of attack in the heavy rain, is that a unique angle of attack dependency  $L$ , or does it depend on past history. Is there a real issue there? I don't think there is. I think we have enough test track, enough time running in the rain that it's not really a problem. I would worry about it if I had a laminar flow air foil, because .. I think I need to Greg a little bit. That's one of the one's I had a hard time answering.

Don Bapin - I'd like to expand on that third question up there. Has anyone considered the implications on the pilot training aides and so on and also on the guidance, if the results from your tests and experiments sort of like the wind tunnel, the lift from the drop (tape difficulty, various individuals speaking, not audible) A: that's the purpose of why we're doing the tests. That's what the interpretation of the wind tunnel results are. That's the way, if you just look at is and say, hey this is what's going to happen, based on that wind tunnel test. What I tried to allude to, you

know, is that interpretation is based on some scaling laws that hasn't been established with regard to this type of testing, so we have to do large scale tests. If the large scale test comes out like the wind tunnel test, then we have a problem I guess and what you tell someone to do in a wind shear environment if he's getting wet at the same time, then the question comes up that like one of the other ones that I've got on here, how wet is he getting at the time you have to be able you'll have to be telling him that. I've got another question .. Say Earl, before you go on, I have one more question briefly again. This thing is really intermittent. Q: Maybe I misunderstood, are the inplates actually connected to your wing section, A: No, they're free floating. Q: So there not part of your balance measurement. A: No.

Q: These are the last two questions I had and top one is regarding Delta flight 191 accident data, a sharp wing drop was recorded at an angle of attack much less than stalled, has this event been correlated with the aircraft that gets exposure to heavy rain. A: I'm going to call a little bit on Dick Gray and I know he worked real closely in this particular accident and looking at the record, I looked at them too and I set down and I talked with Dick. It turns out that my .. as I recollect, the pilot did not stay very long at a very high angle of attack from that data, and I'm not so sure that even when he was at the high angle of attack that correlated with the region when they said he was in heavy rain. We looked at that data set hoping we could learn something from it as a sense of a full scale test and it turns out that the angle of attack that he stayed at were very low and remember the curve and data that I showed you, you would not have seen much in effect at the lower angles of attack. The wing drop .. Dick do you remember when that occurred with respect with the rain and was there something else going on at the same time. The questions that's being asked and let me repeat it for you because I'm sure you can't see it from the back.



It says regarding the Delta flight 191 accident, a sharp wing drop was recorded at an angle of attack much less than stalled. Has this event been correlated with the aircraft's exposure to heavy rain. I would say, based on our data, if it were much less than stalled, we probably wouldn't have seen much a change or change in lift in one wing or either wing. The question, I guess, if you can help us out was do you recall the wing drop, when did it occur? So basically the answer is that they think that most of the motions were wind generated.

Howard Long - Delta Airlines. I've looked at that also very closely, and in that area and from a pilot point of view, what I see happening right at that point is that the guy has encountered the center of a vortex and it's trying to roll the airplane to the right very violently. The control forces that were put in at that point were pull controls to the left for 2 full seconds. The effect that you're doing there is that you have destroyed all the lift or as much as you could off the left wing to keep the thing from rolling upside down, the right wing is in the down draft part of the microburst or part of the vortex, and so you have effectively taken away a lift from both sides of the airplane at the same point, thusly, the nose will start to come down. No body thinks it was rain related. I think that's the basic answer to that. And the last one is from Bob here is, Q: Can you relate liquid water concentration to radar return, can you correlate color weather radar returns with lift loss or reduction in stall speed. A: Well, basically, color weather radars do contour which means they are looking at the concentration of liquid water in front of them and so yes, color weather radars are correlated with liquid water concentration. The purpose of our test for these large scale data is to do that correlation between stall speed reduction in lift with liquid water concentration. Q: This is just as a matter of reference, the liquid water contents that you were using up to 46 grams per cubic meter, are those already a long ways into the red region in a color weather radar return or we looking at anything

pilots might be flying into. A: It would definitely be well into the red region, probably folded over a few times so to speak.

Bill Briar Q: Can you put the picture of the sled back, please for just a second, I have a dumb question to ask. Is there leading edge equipment on that wing? A: It's a fallot double slotted flap. As I said, if you just cut a section right out of the L 1011 wing, it looks a lot like it.

First question from Wayne Sands, Q: Do you see any evidence of pulsing of the microburst velocities in the model? A: No, I have not. I guess I would like to ask Wayne, what if he has seen this on what scales would you usually see this. What's the horizontal scales. The reason I would ask this, is because with this model that I am using, this particular run, we used a grid size of 200 meters meaning that in order to resolve the pulsing if it existed, it would have to be on a scale of at least 400 meters or more, so do you have any ideas?

Q: The different microburst are not visible in plain view? Can you point them out? You are referring to the simulated microburst. A: First, at 47 minutes there was some smaller weaker microburst, I think you can see it up in this region and this was prior to the very intense ones, and somewhat latter, at a later time, you can, of course this was the more intense one in the simulation, there was also another one here and there was one beginning to form in this region. Actually these two here, coalesce together and about four minutes later, you get something that looks like this because they expand into macroburst. So Wayne, does that answer your question?

Q: Also by Wayne Sands. The dual doppler plot of the Denver micro burst seemed more asymmetrical than the wind fields generated by the model. Please discuss. Q: Well first, I would start off asking the question to Wayne, what elevation are you looking at and what's your beam width at that particular point. A: We're just looking at the low level tilt and it's a one degree beam width, it's a few hundred meters off the ground like 300 or thereabout, I might defer to Jim Evans for the number, but that's the right order. So, you would say somewhere from 200 to 300 meters. Well, the reason I ask that is because as you go up in elevation, not only in this case but in other cases that I have seen, the flow tends to become more asymmetric. The microburst from other simulation that I've seen also appear to have the most symmetrical qualities at my lowest level, and this level as you can see is 80 meters off the ground. But, as you were to go up in elevation, it would appear more asymmetrical, part of that being due to the depths of the out flow are somewhat deeper in certain areas and the velocities may be more intense on certain sides so you will see this. Unfortunately, I don't have any plots with me of the outflow at 200 and 300 meters but there are differences. Too, I'll point out this is the elevation where we do tend to see the most intense out flow speed anywhere in between say, 50 meters off the ground to about 100 meters above the ground for microburst.

Q: Question from an unknown author. There were a number of microburst in the area, prior to and following the simulation. These did not show surface winds greater than 20 meters per second, yet presumably, had the same sounding environment. Q: How would this difference between microburst emerge from the simulation? A: Well first of all, I would say, there probably is a lot of differences in the environment as you would go across the area. Now, what I have used to initialize my simulation was a modification of the 20z Denver sounding, I modified it to agree in the barrender layer with the observed 22z Denver temperature or temperature just prior to 22z it was about that time. Now, I haven't done any kind of sensitivities studies on say, what

would happen if the temperature or the moisture in the boundary layer was a little bit different. Now, that could certainly affect the intensity of the storm, or the structure of the storm. And when I did run this simulation, I was a bit concerned also with using the winds from the 20z sounding which was 2 hours prior to the event. In other words, if there were some slight changes in the winds, they certainly could have affected the structure of the actual storm, versus that of the simulated storm. But, I think you have to keep in mind that this is not a replication of an observed event, although, I think we're simulating a lot of the features very well. Don't look at it as an embedded mesh forecast of the Denver area. I think that may have answered the second question. Oh, the second question, how have you compared the simulation results with radar measurements. Today, was the first day that I've seen any of the observations so I haven't compared anything yet. Does anyone have anything else?

Meeting concluded 18 Oct 88.

# **TECHNICAL PRESENTATIONS**

**Wednesday, 19 October 1988**

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## **Session I. Airborne—Sensors**

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## **Session I. Airborne-Sensors**

**Airborne Doppler Radar Detection of Low Altitude Wind Shear**  
**E. M. Bracalente and W. R. Jones, NASA LaRC**  
**Charles L. Britt, RTI**

# **AIRBORNE DOPPLER RADAR DETECTION OF LOW ALTITUDE WINDSHEAR**

Emedio M. Bracalente, William R. Jones  
NASA Langley Research Center  
Hampton, Va. 23665

And

Charles L. Britt  
Research Triangle Institute  
Hampton, Va. 23665

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# AIRBORNE DOPPLER RADAR DETECTION OF LOW ALTITUDE WINDSHEAR

E.M. BRACALENTE, C.L. BRITT\*, W.R. JONES  
NASA LANGLEY RESEARCH CENTER, HAMPTON, VA.  
23665

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## Abstract

As part of an integrated windshear program, the Federal Aviation Administration, jointly with NASA, is sponsoring a research effort to develop airborne sensor technology for the detection of low altitude windshear during aircraft take-off and landing. One sensor being considered is microwave Doppler radar operating at X-band or above. Using a Microburst/Clutter/Radar simulation program, a preliminary feasibility study was conducted to assess the performance of Doppler radars for this application. Preliminary results from this study are presented. Analysis show, that using bin-to-bin AGC, clutter filtering, limited detection range, and suitable antenna tilt management, windshear from a "wet" microburst can be accurately detected 10 to 65 seconds (.75 to 5 Km) in front of the aircraft. Although a performance improvement can be obtained at higher frequency, the baseline X-band system simulated detected the presence of a windshear hazard for the "dry" microburst. Although this study indicates the feasibility of using an airborne Doppler radar to detect low altitude microburst windshear, further detailed studies -- including future flight experiments -- will be required to completely characterize the capabilities and limitations.

## Key Words

Aviation safety, windshear detection and avoidance, windshear hazard index, airborne remote sensor technology, microwave Doppler radar.

## Nomenclature

A/D	Analog to Digital
AGC	Automatic Gain Control
A/C	Aircraft
c	Speed of light, m/s
CSD	Clutter Spectral Density
CSR	Clutter-to-Signal ratio
D	Rain drop diameter, mm
dB	Decibels
dBw	Decibels relative to 1 watt
dBz	Reflectivity factor in Decibels
F	Hazard factor
F <sub>R</sub>	Radial component of hazard factor
g	Acceleration of gravity, m/s <sup>2</sup>
G	Peak antenna gain
I&Q	In-phase and Quadrature
k	Boltzmann's constant, Joules/Kelvin
k <sub>w</sub>	Refractive index factor for rain

l	One-way rain attenuation loss
l <sub>r</sub>	Receiver bandwidth loss factor
ln	Natural log (to the base e)
n	Total rain reflectivity per unit volume
NRCS	Normalized Radar Cross Section
P <sub>n</sub>	System noise power, watts
P <sub>s</sub>	Reflected signal power, watts
P <sub>t</sub>	Peak transmitter power, watts
PRF	Pulse Repetition Frequency
R <sub>g</sub>	Range bin distance from A/C, m
R <sub>T</sub>	Range to target, meters
SAR	Synthetic Aperture Radar
SCR	Signal-to-Clutter ratio
SNR	Signal-to-noise ratio
T <sub>s</sub>	System Noise Temperature, deg. Kelvin
Tilt	Antenna angle measured from A/C glide-slope
V	Aircraft airspeed, m/s
V <sub>c</sub>	Cell volume of rain target, m <sup>3</sup>
W <sub>h</sub>	Vertical component of inertial wind, m/s
W <sub>x</sub>	Horizontal component of inertial wind, m/s
Z <sub>e</sub>	Reflectivity factor, mm <sup>6</sup> /m <sup>3</sup>
τ	Transmitter pulse duration, sec.
φ	Antenna 3 dB beamwidth, radians
λ	Wavelength, meters

## I. Introduction

Low altitude microburst windshear is recognized as a major hazard during takeoff and landing of aircraft. Microbursts are relatively small, intense downdrafts which spread out in all directions upon striking the ground. When such windshear is encountered at low altitudes during landing or takeoff, the pilot has little time to react correctly to maintain safe flight (Fig. 1). In the United States during the period 1964 to 1985, there were 26 major civil transport aircraft accidents and four incidents involving 626 fatalities and over 200 injuries for which windshear was a direct cause or a contributing factor. As part of its integrated windshear program, the Federal Aviation Administration (FAA) jointly with NASA, is sponsoring a research effort to develop airborne sensor technology for detection of low altitude windshear during A/C takeoff or landing. A primary requirement for an airborne forward-looking sensor or system of sensors is to be capable of detecting both heavy ("wet") and light ("dry") precipitation microbursts. One sensor being considered for this application is microwave Doppler radar operating at X-band or higher frequency. Since absolutely clear air produces no radar return at microwave frequencies except very slight scattering from gradients in the index of refraction on the scale of the r.f. wavelength, the emphasis in the present research is on those microburst containing at least some liquid water.

\*Affiliation: Research Triangle Inst.,  
Hampton, VA

Previous experiments<sup>1</sup> and studies have demonstrated, in a limited way, the capability of airborne Doppler radars to detect the presence of windshear. However, for A/C landing and take-off applications, the problems of severe ground clutter, rain attenuation, and low reflectivity levels must be solved. To consider these problems, a Microburst/Clutter/Radar simulation program has been developed to aid in the evaluation and development of Doppler radar concepts. The simulation program incorporates windfield and reflectivity databases derived from a high resolution numerical windshear model<sup>2</sup>, clutter maps derived from airborne Synthetic Aperture Radar (SAR) backscatter data, and various airborne Doppler radar configurations and signal processing concepts. The program simulates the operation of a Doppler radar located in an A/C approaching a runway, sensing signal returns from a windshear microburst and an airport clutter environment. A description of the Microburst/Clutter/Radar simulation program is presented along with examples of simulation outputs.

Using this program, a preliminary tradeoff and assessment study was conducted to evaluate the performance of Doppler radars to detect windshear during A/C landing. Case study results for a strawman design are presented, illustrating airborne Doppler radar capabilities. Results for both a "wet" and "dry" microburst are included. This preliminary study shows the feasibility of using airborne Doppler radars to detect windshear; however, further detailed studies will be required, including future flight experiments, to completely characterize their capabilities and limitations.

## II. Doppler Radar Design Requirements and Performance Tradeoffs

### Preliminary Design Requirements

A preliminary set of performance requirements<sup>3</sup> has been established for design of forward-looking windshear detection sensors. The sensors' primary requirement is to detect severe microburst windshear during final approach to landing (Fig. 1) or during takeoff, and to provide as a minimum, 15 to 40 seconds (approximately 1 to 3 km) warning to the pilot. Advisory information on windshear conditions 50 to 100 seconds (4 to 8 km) in front of the A/C is also desired. The sensor or sensor system must be able to detect windshear caused by both heavy and light precipitation microbursts. The sensor must measure mean horizontal wind speeds every 150 to 300 meters out to a range of 6 to 8 km along the flight path and a small sector (approx. 20 deg.) on either side of the A/C, with approximately 1 m/s accuracy. These primary requirements have been established as minimum guidelines for developing sensor design requirements and evaluating potential concepts. The requirements to provide other information and capabilities, such as vertical wind speeds, rain reflectivity, wind turbulence, microburst signature recognition, and various display capabilities have not been established. Guidelines for these requirements are being developed.

A major area of radar design that requires extensive development is the radar signal processing technique, which will suppress clutter interference and provide maximum windshear detection accuracy. Before these techniques can be developed and evaluated, radar parameters must be chosen and evaluated. The radar parameters chosen by the radar designer are those which go in the radar equation to compute Signal-to-Noise Ratio (SNR) performance. The SNR for a signal reflected from a distant rain cell target is approximated by the following equations:<sup>4</sup>

$$SNR = \frac{P_s}{P_n} = \frac{P_t G^2 l^2 l_r \lambda^2 n v_c \tau}{2 \ln(2) (4\pi)^3 k T_s R_T^4} \quad (1)$$

where:

$$P_n = k T_s / \tau \quad (2)$$

$$n = 10^{-18} (\pi^5 / \lambda^4) |k_w|^2 Z_e \quad (3)$$

$$Z_e = (1 / \Delta v_c) \sum_j D_j^6 \quad (4)$$

$$v_c = (\pi / 4) R_T^2 \phi^2 (c \tau / 2) \quad (5)$$

As seen from these equations a large number of parameters affect the performance of the radar. The designer, however, has control over only a few of them, mainly transmitter power, antenna gain, frequency of operation, pulse duration, and to a minor degree, target range. There is, for airborne operation, a number of factors which limits the choice of values for these parameters. The use of higher operating frequencies provides greater sensitivity to rain reflectivity<sup>(3)</sup> and higher resolution<sup>(5)</sup>, but is subject to greater attenuation by rain. Most operational Doppler weather radars operate at frequencies of S-band (1-3 GHz), C-band (3-8 GHz), and X-band (8-12 GHz). Although negligible attenuation occurs at S-band, the increase in sensitivity and smaller cell resolution at X-band outweighs the small increase in attenuation (2-5dB) experienced for "wet" microbursts. For "dry" microbursts, frequencies in the Ku-band (12-18 GHz) region could be considered since attenuation would remain low. Windshear detection capability for both "wet" and "dry" microbursts could utilize dual frequency operation, but practical considerations make it desirable to find one frequency that can provide acceptable performance for all microbursts.

Airborne weather radars, operate in an allocated frequency band around 9.3 GHz and utilize solid state transmitters of about 100 watts. They are presently in use to display rain reflectivity and wind turbulence advisory information to the pilot. Therefore, it is of interest to assess airborne Doppler radar concepts for windshear detection operating in this frequency band utilizing relatively low powers. Space limitation in the nose radome of passenger A/C limit the maximum antenna size to about 30-36 inches (.76-.91 m) in larger A/C and about 18-20 inch in smaller A/C. This makes it more important, from a resolution and sensitivity standpoint, to operate at the higher frequencies. It is desirable to keep transmitter power requirements low so that solid state transmitters can be considered. Other radar parameters such as pulse repetition frequency (PRF), and pulse width are chosen to minimize velocity and range foldover problems and to provide acceptable range resolution. Table 1 lists the range of radar parameter values being considered in the feasibility study, and which represent state-of-the-art airborne Doppler radar hardware implementation capability. Also listed is a baseline set of values used in the initial radar simulation case studies.

Table 1 Wind shear Doppler radar parameter values

Parameter	Baseline Value	Tradeoff Range
Pulse repetition freq. (PRF)	3030	2000-5500
Pulse width (TAU) u-sec.	1.0	1.0 -3.0
Max. det. range, km	10	5 TO 10
Range gate resolution, m	150	150 TO 450
Range sampling window, km	1-9	1-10
Max. unambiguous ws, m/sec.	24	24 TO 45
Wind speed accuracy, m/sec.	1.0	.5 TO 2
Operating frequency, GHz	9.3	9.3 - 15
Antenna diameter, m	.76	.46-.91
Antenna gain, dB	35.5	31 TO 48
Antenna beamwidth, deg.	3	.8 TO 5
Sidelobe level, dB	< -25	-20 TO -35
Antenna polarization	LINEAR H	DUAL POL
Ant. tilt angle range, deg.	0 to 2	0 to 20
Azimuth angle range, deg.	+OR- 21	+OR- 45
Minimum det. signal, dBZ	0	-15 TO 10
Transmitter peak power, kw	2	.2 to 10
System noise figure, dB	4	3 TO 6
Return sig. dynam. range, dB	70	60 - 80
Receiver dynamic range, dB	50	45 TO 55
Xmit/rec. phase jitter, d.rms	.5	.1 TO 2
Number of A/D conv. bits	12	10 TO 14
Clutter filter type	2 pole	TBD
Processing technique	PP	FFT, PP

## SNR Performance

Using selected values of parameters found in table 1, a set of SNR performance curves were computed using (1). Sample plots of these SNR curves are shown in figures 2 & 3. The SNR is computed in a bandwidth equal to  $1/T$ . A SNR in this bandwidth of greater than unity (0 dB) is generally required to obtain adequate Doppler processing performance. These curves show that SNR performance exceeding 0 dB can be obtained for relatively low reflectivity levels (0 to 10 dBZ) for ranges out to 10 km. Reflectivity values range from 60 dBZ in the core of "wet" microbursts, to 10 to 40 dBZ in the outflow region. The performance curves for both the 9.3 GHz (fig. 2) and 15 GHz (fig. 3) show more than sufficient SNR performance for these ranges of reflectivities. For "dry" microbursts the core reflectivity can be in the range of 20 to 30 dBZ range, falling to -20 to +5 dBZ in the outflow region. The 9.3 and 15 GHz performance for a -10 dBZ reflectivity falls below 0 dB SNR at about 3 km and 6 km respectively, which are still acceptable ranges for this application. An increase in transmitter power would be required to operate down to the -20 dBZ level.

## Clutter Performance

The X and Ku-band SNR performance was shown in the previous section to be more than sufficient to allow adequate Doppler processing. However, one of the major problems associated with the sensing of microburst using an airborne Doppler radar is the presence of ground clutter. To assess the magnitude of this problem, an analysis of clutter spectra and clutter-to-signal (CSR) ratios was conducted, using ground clutter maps derived from well-calibrated SAR Normalized Radar Cross Section (NRCS) data as described in section III. A set of clutter maps has been produced for a number of different airports from existing sets of SAR data. Figures 4 & 5 show sample clutter-to-signal (CSR) ratio results, assuming a 10 dBZ rain reflectivity signal level, for a few sample radar configurations approaching Willow Run airport. Plots are shown for a 5 km A/C range from touchdown, antenna tilt angles of 0° and 2° (antenna angle measured up from the A/C glide-slope of -3°), and antenna azimuth angles of 0° and 10°. Table 2 lists the radar parameters used in these analyses. Figure 6 shows a histogram plot of the range of NRCS levels which exist in the clutter map used. The NRCS levels larger than -10 dB come primarily from urban areas and high level discrete targets.

Table 2 Radar parameters used in clutter analysis

A/C range from runway	-- 5 & 7 km
A/C ground velocity	---- 77 m/s
A/C glide slope	----- 3°
Frequency	----- 9.3 GHz
Antenna Dia.	----- .76 m (30 in.)
Antenna edge illum.	---- -10 dB
Rain Reflectivity	----- 10 dBZ
Pulse width	----- 1 u-sec.
PRF	----- 5000
Ant. tilt angle	----- 0 & 2 deg.
Ant. azimuth angle	----- 0 & 10 deg.

### III. RADAR SIMULATION

The results of this preliminary clutter analysis show that the highest clutter levels (CSR of 30-60 dB) occur where the pulse in the main beam intersects the ground, from the urban areas, and for antenna tilt angle of  $0^\circ$ . Two significant results are shown by these analyses, which can be utilized to greatly reduce the effects of clutter. First, lower CSR values occur at short ranges in front of the A/C, at range gates where the pulse in the main beam has not touched the ground. At these ranges the clutter is coming primarily from sidelobes, which if sufficiently low will suppress the clutter signals. For a  $3^\circ$  beamwidth antenna pointed down at a  $0^\circ$  tilt angle and a 5 km A/C range, the -3 dB point of the main beam first touches the ground at about 3.5 km, and the first sidelobe null point at about 2.7 km (a point about 35 seconds ahead of the aircraft). For a  $2^\circ$  tilt these points are about 6 and 4.3 km respectively. Note in figure 4 the increase in CSR at a range of 2.5 km. This point corresponds to NRCS levels of -5 to 0 dB from a residential area about 2.5 to 3 km from the runway. The clutter level would have been much higher had the main beam been viewing this area rather than the beam sidelobes.

A second fact that is very evident in the data is the significant reduction in clutter that occurs when the antenna is tilted up from  $0^\circ$  to  $2^\circ$ . Thus, by limiting the range of data processing and employing proper antenna tilt control, CSR levels can be kept below 40 dB (well within the dynamic range capabilities of present day Doppler radar receiver design technology). Clutter suppression techniques can then be employed to reduce clutter to acceptable levels. Figure 7 shows a sample clutter spectral density plot for the 2.5 km range gates of figure 4 (ant. Tilt= $2^\circ$ , Az= $0^\circ$ , A/C at 5 km). The density levels are plotted against velocity relative to the A/C's ground velocity. With the most significant clutter spectrum energy levels contained between zero and about 4 m/s, a high pass filter with maximum attenuation at zero velocity can be employed to significantly reduce the clutter levels. The CSR shown in figure 7 will be reduced by over 25 dB if the energy below 3 m/s is filtered out. Since the most severe wind velocities of interest exist at much higher speeds (5-30 m/s), this filter will have little effect on the wind speed velocity estimation. Studies are underway to evaluate filter processing techniques which can provide optimum results. Section IV presents sample case study results of windshear detection performance, using the radar simulation program.

#### General Description

The radar simulation program is a comprehensive calculation of the expected output of an airborne coherent pulsed Doppler radar system viewing a low-level microburst along or near the approach path of the aircraft. Figure 8 is a block diagram showing the major features of the simulation. Inputs to the program include the radar system parameters and large data files that contain the characteristics of the ground clutter and the microburst. The ground clutter data file consists of high-resolution (20m) calibrated Synthetic Aperture Radar (SAR) data of selected airport areas. The microburst data files provide reflectivity factors, x,y,z wind velocity components, and other meteorological parameters with a resolution of 40 meters. This database is generated by a numerical convective cloud model<sup>2</sup> driven by experimentally-determined initial conditions, and represents selected time periods of the microburst development.

For each range bin, the simulation calculates the received signal amplitude level by integrating the product of the antenna gain pattern and scattering source amplitude and phase over a spherical-shell volume segment defined by the pulse width, radar range and ground plane intersection. The amplitude of the return from each incremental scatterer in the volume segment is proportional to either the square root of the normalized cross-section of the ground clutter (from the clutter map) or the square root of the reflectivity factor of the water droplets in the microburst (from the microburst data base). The phase of each incremental scatterer is the sum of a uniformly distributed (0 -  $2\pi$ ) random phase term, a phase term due to relative aircraft-scatterer radial velocity, and normally-distributed random phase terms representing transmitter/receiver phase jitter and ground clutter random motion. The random phase terms simulating phase jitter and ground clutter motion are updated for each transmitted pulse, while the uniformly-distributed phase terms are updated for each sequence of pulses in a range bin. The phase terms representing aircraft-scatterer relative motion are linear functions of time.

Path attenuation for each incremental scatterer is determined by integrating the path losses over the transmission path. Empirical formulas<sup>4</sup> are used to determine the incremental path losses from the liquid water content of the microburst. Aircraft ground velocity is assumed to be known accurately so that derived Doppler frequencies can be referenced to a value of zero corresponding to that velocity.

Antenna patterns simulated include a generic parabolic antenna with size and aperture illumination taper specified by input data, and a flat-plate array antenna with a pattern similar to that found in the current generation of X-band airborne weather radars.

In the simulation, a sequence of N pulses of in-phase (I) and quadrature (Q) signal amplitudes are calculated for each range bin as discussed above and subjected to AGC amplification and A/D quantization. A simulated fast-acting AGC is used to adjust the gain of the system on a bin-by-bin basis to achieve a wide dynamic range and to prevent signal saturation (due to clutter) prior to and during A/D conversion. The I and Q pulse stream is then digitally filtered to suppress ground clutter near zero Doppler frequencies and processed using both conventional pulse-pair and spectral averaging algorithms to derive the average velocity and spectral width of the scatterers in the range bin. Further processing of the velocity data provides information on windshear and aircraft hazard factor.

Provision is made in the simulation to generate returns from a specified number of range bins over a specified azimuth scan so that simulated color displays of reflectivity, velocity, windshear, spectral width, etc., can be examined. Other outputs of the simulation include plots of power levels, velocity, spectral width, windshear hazard factor, and AGC levels vs. radar range. Doppler spectra of ground clutter and moisture as derived from the I and Q signals from each simulated range bin are also plotted.

#### Microburst Model

As mentioned above, the microburst model is a detailed numerical convective cloud and storm model that calculates the time history of the development of a microburst. The model uses a nonhydrostatic, compressible and unsteady set of governing equations which are solved on a three-dimensional staggered grid. The computation can be initiated from observed data and generates realistic wind fields that compare favorably with observed data such as that obtained in the JAWS study<sup>5</sup>. For the radar simulations to date, a 4x4 km lattice of 40x40 meter grid spacing increments (two-dimensional axisymmetric version) has been generated at selected time periods. Output parameters include the radar reflectivity factor (dBz), wind velocity components, temperature, equivalent potential temperature, pressure and moisture content (water vapor, ice, cloud droplets, rain, snow and hail/graupel). The model developed under NASA sponsorship is described in detail in references 2 and 5.

For the radar simulation cases discussed in this paper, a typical "wet" microburst and a typical "dry" microburst were selected and used to investigate radar performance at a particular instant of time. Figure 9 shows the reflectivity factors and velocity field of the axisymmetric "wet" microburst used in the radar simulation. The "dry" microburst is similar in form but with smaller dimensions, lower wind speeds, and much lower reflectivity levels. The "wet" microburst data are taken at 11 minutes after initiation of the microburst calculation and the "dry" microburst data are 23 minutes after initiation. The "wet" microburst resembles an axisymmetric version of the 2 August, 1985, Dallas-Ft. Worth storm<sup>6</sup> and the "dry" microburst is based on soundings taken on 14 July, 1982, within the JAWS network near Denver.

#### Clutter Model

The ground clutter model used for the present simulation cases is a high-resolution X-band SAR map of the Willow Run, Michigan, airport area provided by the Environmental Research Institute of Michigan (ERIM).

The SAR image files produced by ERIM provide calibrated NRCS data with a resolution of 20m. Figure 10 shows a high resolution (3m) SAR image of Willow Run airport from which this data was derived and the runway (9R) used in the simulation runs. In the simulations, the aircraft is positioned at a selected distance from the runway touchdown point on a three-degree glide slope.

A problem with the use of existing SAR data is associated with the variation of cross section with depression angle. These data were taken at depression angles ranging from approximately 18 to 50 degrees, whereas for the operational airborne radar simulated the depression angles of interest are approximately 1 to 20 degrees. To partially account for this difference, ERIM supplied an empirical depression-angle correction function that corrects the NRCS to the angle seen by the airborne radar. Since clutter sources from urban areas have cross sections that do not decrease significantly with depression angles in the ranges of interest, urban areas of the clutter map are excluded from this depression angle correction and the originally measured cross-section values are used in the simulation. Also, areas of the map with NRCS values equal to or greater than 5 dB are not corrected.

The corrections for depression angle are not entirely satisfactory, and cause an uncertainty in the clutter calculations of the preliminary cases discussed in this paper. Flight experiments using the ERIM SAR instrument will be flown in the summer and fall of 1988 to collect more representative airport clutter data with depression angles corresponding to those that would be seen by an airborne radar on the approach path. These data will provide better information of depression angle variation of NRCS for urban environments as well as other surfaces.

#### IV. SIMULATED RADAR PERFORMANCE

##### "Wet" Microburst

To examine the expected radar performance in specific situations, several cases have been simulated, as illustrated in figure 1, using the baseline system parameters given in table 1 and the ground clutter map from the Willow Run airport area. Figure 11 plots the SNR and SCR vs. radar range for a "wet" microburst that would be seen by the radar at a distance of 7 km from the runway touchdown point with the antenna tilted up 2 deg from the projected aircraft path. The microburst axis is located on the projected path 2 km from the touchdown point. The calculated reflectivity factor of the water droplets along a line corresponding to the projected aircraft path is also plotted in figure 11 for comparison to the simulated radar measurements. For this case, the SNR and SCR are high over the entire region of the microburst, with a minimum value of SCR (10dB) occurring at approximately 3 km from touchdown. This minimum value is due to high clutter power from an urban area at this location. The SNR exceeds 20 dB over the range, with approximately 18 dB difference between the near side and far side of the microburst due to path attenuation and geometrical factors (in this plot, the power levels are not corrected for the  $R_T^2$  loss).

Figure 12 shows the calculation of the radial component of wind velocity derived from both pulse-pair and spectral averaging algorithms operating on 128 simulated I and Q pulses from the radar. This figure also plots, for comparison, the "true" wind speed, defined as the velocity component along the center line of the antenna beam. It should be noted that the true velocity, as defined, will always differ somewhat from the radar-measured velocity because the true velocity is measured along a line (the antenna center line), whereas the radar system measures a weighted (by reflectivity and antenna pattern) average of the velocity over a finite volume of the microburst.

A two-pole high-pass Butterworth filter was used to filter the I and Q pulses to suppress ground clutter. The 6 dB frequency response cutoff point is located at a Doppler frequency --relative to the A/C ground velocity-- corresponding to a radial component of wind velocity of 3 m/s, and the filter has two zeros at zero Doppler frequency. The effect of the clutter filter can be seen in figure 13, which is a plot of the Doppler spectrum in a range bin 4 km from the radar calculated with and without the clutter filter. For simulated velocity measurements, a processing threshold of 4 dB is used (i.e., the pulse-pair and spectral averaged velocities are set to zero if the radar received power is less than 4 dB greater than the noise threshold).

The simulated velocity measurements are within 2 m/s of the "true" velocity for velocities greater than 5 m/s and indicate clearly the potentially hazardous windshear associated with the microburst. To more closely indicate the windshear hazard to the aircraft, a measure called the F-factor or hazard index has been defined by Bowles.<sup>3</sup> This index is defined by the equation:

$$F = \frac{W_x}{g} - \frac{W_h}{V} \quad (6)$$

where  $W_x$  is the rate of change of the component of wind velocity along the aircraft path,  $g$  is the acceleration of gravity,  $W_h$  is the vertical component of wind velocity and  $V$  is the aircraft velocity. Values of  $F$  greater than 0.1 to 0.15 are considered hazardous to jet transport aircraft, considering aircraft type, configuration, and range of gross weights.<sup>3</sup>

Although a forward-looking radar sensor cannot directly measure the vertical wind component, the radial velocity component is measured directly. The first term in the equation for the F-factor can be derived from radar measurements of radial velocity as follows:

$$\text{Let } W_x = V \frac{\delta W_x}{\delta R_g} \quad (7)$$

$$\text{then } F_R = \frac{V - \delta W_x}{g \delta R_g} \quad (8)$$

where:

$\delta W_x$  = change in radial velocity between adjacent range bins

$\delta R_g$  = distance between range bins

$F_R$  = the radial component of the hazard index

This radial term is calculated in the simulation from the velocity measurements as shown in figure 12 by averaging velocity differences over 5 range bins, and results in outputs as shown in figure 14. The radial term of the hazard factor reaches a maximum value of 0.1 for this microburst, and both pulse-pair and spectral averaging algorithms give good measurements of the factor.

### "Dry" Microburst

Simulation runs similar to those discussed above were also made with the "dry" microburst discussed previously. Figure 15 shows the hazard index derived by these runs using the baseline system parameters operating at 9.3 GHz. The figure indicates that although the windshear was detected, the velocity measurement with the baseline set of system parameters was somewhat noisy.

To improve the performance on the "dry" microburst, several system parameters can be changed. These trade-off studies have just been initiated. For example, to illustrate the radar performance at Ku-band, the dry microburst case discussed above was simulated using the same set of baseline parameters, except the operating frequency was changed to 15 GHz and the PRF was changed to 4878 pulses per second. Results for the Ku-band system with the dry microburst are shown in figures 16, 17, and 18. As may be seen, even though the SNR and SCR values are much lower than those with the wet microburst, the wind velocity was successfully measured over the hazardous part of the microburst. The hazard factor calculation clearly indicates the windshear hazard associated with this microburst.

### Simulated Displays

The radar simulation program provides for an azimuth scan mode and the generation of simulated displays of several variables of interest. Figure 19 shows a black and white copy of a simulated (color) display of radial wind velocity for the "wet" microburst with the baseline set of radar parameters. Figure 20 is a simulated plot of the radial term of the F-factor and clearly indicates that a potential windshear hazard lies on the aircraft path. These displays should not be interpreted as recommended displays for the aircrew, since the specific method of alerting the crew to a hazard requires extensive study, which is presently under way, and will most likely consist of a warning light or alarm which may be supplemented by displays of additional information to aid the aircrew's decision-making process.

### Future Simulation Development

The simulation program will be improved in the near future by incorporating more sophisticated signal processing techniques, models to represent moving ground clutter, and techniques for estimating true, nuisance, and missed hazard alarms. Considerable effort is planned to incorporate and investigate a full range of microburst/clutter environments, provide improved displays of simulation output data for evaluating performance, and to conduct extensive tradeoff and optimization studies.

### V. Concluding Remarks

A preliminary tradeoff and assessment study was conducted to evaluate the performance of airborne Doppler radar sensors to detect hazardous microburst windshear during A/C landing. Using a preliminary set of performance requirements for the design of forward-looking sensors, a baseline set of radar parameters was developed for use in assessing windshear detection performance using a radar simulation program. A description was given of the simulation program, which includes excellent models of microburst wind fields, realistic clutter maps of airports, and accurate models of Doppler radar operation and signal processing.

For the baseline Doppler radar sensor configurations modeled, preliminary analyses of the computer simulation case studies show that windshear can be accurately detected 10 to 65 seconds in front of the aircraft approaching a hazardous microburst positioned in the flight path of landing aircraft. This was accomplished using a bin-to-bin AGC, clutter filtering, limited detection range, and suitable tilt management. The sensor is highly effective for the "wet" microburst where very high SNR and SCR are obtainable due to large reflectivity levels. For the "dry" microburst, with low reflectivity levels, windshear was detected, however, more tradeoff analyses and signal processing studies are needed before the performance for the "dry" microburst case can be fully assessed.

Initial simulations were conducted with a specific airport, selected microburst time instants, and the baseline radar parameters. These simulations clearly show that in realistic situations, downward-looking airborne radar sensors have the potential to detect windshear and provide information to the aircrew that will permit escape or avoidance of hazardous shear situations. Plans are underway to investigate a full range of microburst/clutter environments, conduct extensive tradeoff and optimization studies, and investigate various signal processing and clutter filtering concepts which can provide reliable windshear detection capability.

The initial simulation studies were confined to the landing approach, since it presents the most severe signal-to-clutter situation. Studies of the takeoff case are planned. Since the antenna can be tilted up, therefore providing high signal-to-clutter ratios, acceptable detection performance is anticipated for this case.

Although hazardous windshear can be detected by Doppler radar, the pilot must be alerted in a timely manner to avoid the hazard. A hazard index has been developed<sup>3</sup> which establishes when a threat to the performance of the A/C exists. The simulation studies showed that a Doppler radar sensor can detect the horizontal component of this index with sufficient accuracy to indicate in a timely manner that a threat exists. Further studies using this index will be conducted for various microburst types and locations relative to the A/C to assess the missed and nuisance alarm rate. Displays of additional advisory information for the aircrew will probably be required, and are under study. Output display examples from the simulation studies represent some of the information that could be provided.

The present and future simulation studies will provide a good foundation to determine the capabilities and limitations of Doppler radar concepts for the detection of microburst windshear. Flight experiments are needed to evaluate the simulation modeling and performance estimates. A flight experiment program is planned for the 1990-91 time period. The first phase of flights will involve measuring the clutter environment from selected airports during landing approaches. These data will be used to evaluate the clutter map models derived from the SAR data. A second phase of flights will collect data from severe convective storms at altitudes above 2000 feet. These data will be combined with the clutter data to be used to evaluate the performance of various signal processing concepts. Flight tests for candidate concept evaluation and demonstration would follow.

## VI. References

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2. Proctor, F. H.: "The Terminal Area Simulation System Vol. I: Theoretical Formulation." NASA CR 4046: DOT/FAA/PM-86/50, I. April 1987
3. Bowles, R. L.; and Targ, R.: "Windshear Detection and Avoidance: Airborne Systems Perspective." Presented at 16th Congress of the ICAS Aug 28-Sept 2, 1988, Jerusalem, Israel.
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5. Proctor, F. H.: "The Terminal Area Simulation System Vol. II: Verification Cases." NASA CR 4047: DOT/FAA/PM-86/50, II. April 1987
6. Bowles, R. L.: "Windshear Modeling: DFW Case Study", presented at conference "Windshear Detection Forward-Looking Sensor Technology", NASA CP 10004: DOT/FAA/PS-87/2, Oct. 1987

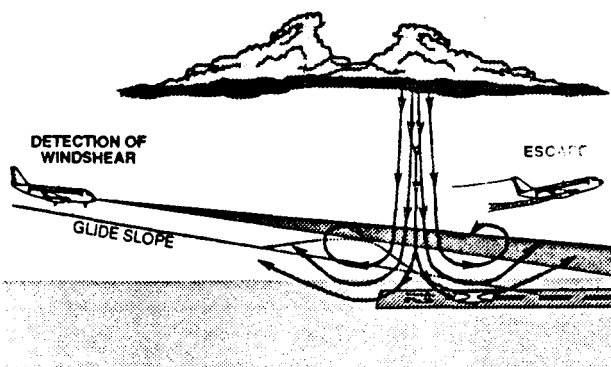


Fig. 1 Sketch illustrating the microburst windshear hazard for an approaching A/C, being probed by a radar beam. Potential impact path is shown if escape or avoidance maneuver is not activated.

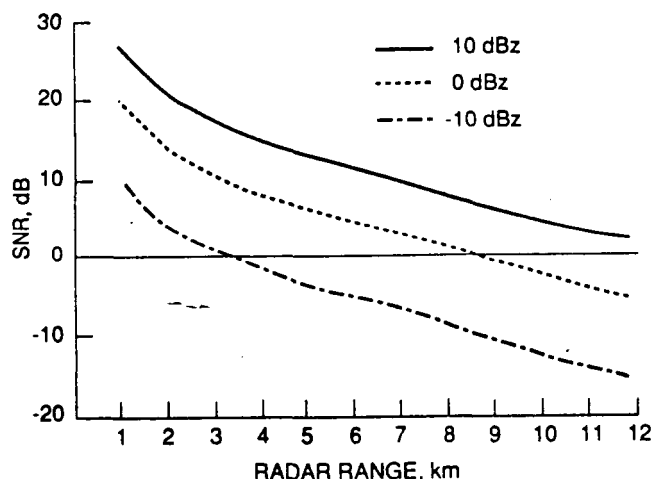


Fig. 2 Signal-to-Noise performance for different reflectivity levels, A/C 10 km from touchdown, 9.3 GHz,  $P_T=2$  kw,  $T=1$  us, Ant. Dia.=30 in., Tilt= $0^\circ$

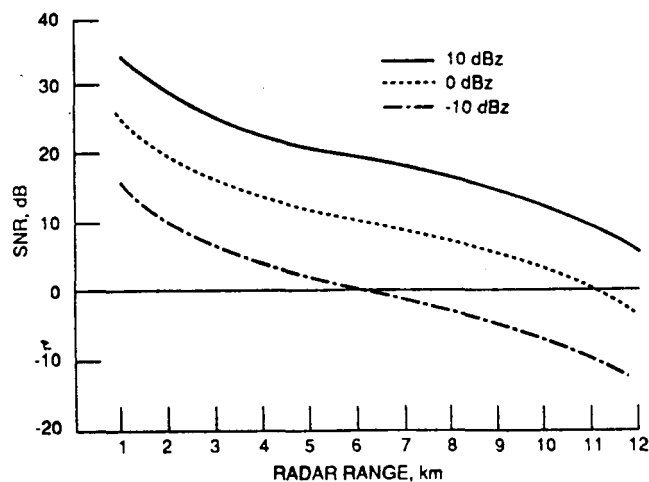


Fig. 3 Signal-to-Noise performance for for 15 GHz. All other conditions the same as in Fig. 2.



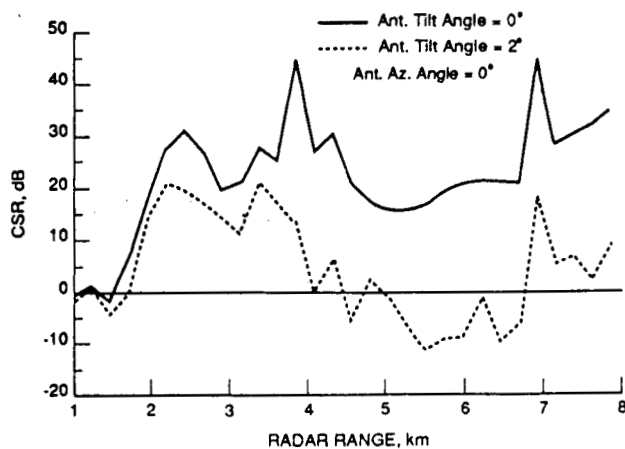


Fig. 4 Clutter-to-Signal (CSR) vs range from A/C, using Willow Run clutter map. A/C 5 km from touchdown, Ant. Az angle=0°,  $Z_e=10$  dBz. See table 2 for other parameter values.

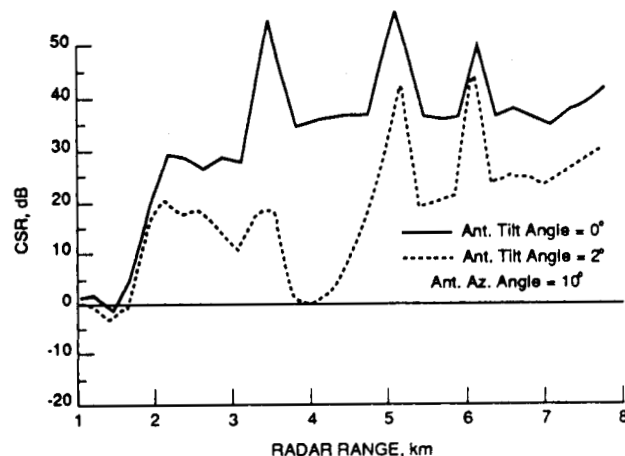


Fig. 5 Clutter-to-Signal (CSR) vs range from A/C for same conditions as fig. 4 except Ant. Az angle = 10°

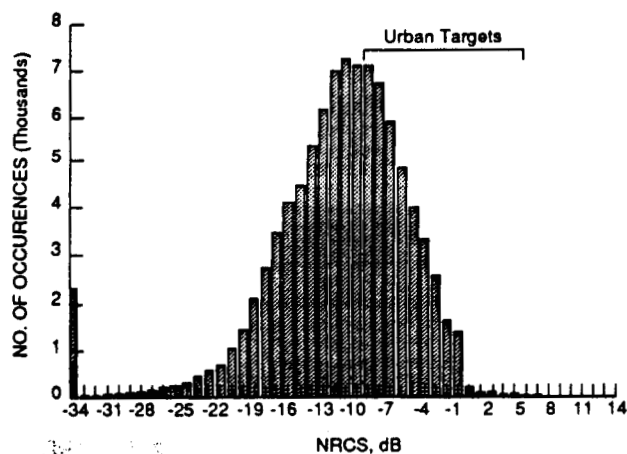


Fig. 6 Histogram plot of range of NRCS levels contained in the Willow Run Airport clutter map.

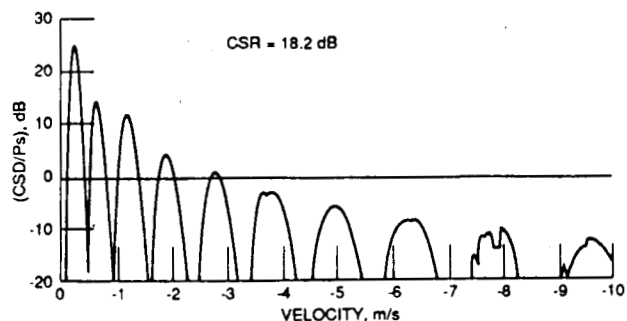


Fig. 7 Normalized clutter spectral density plot for 2.5 km range bin. A/C 5 km from touchdown, Ant. Tilt=2°, Az=0°,  $Z_e=10$  dBz

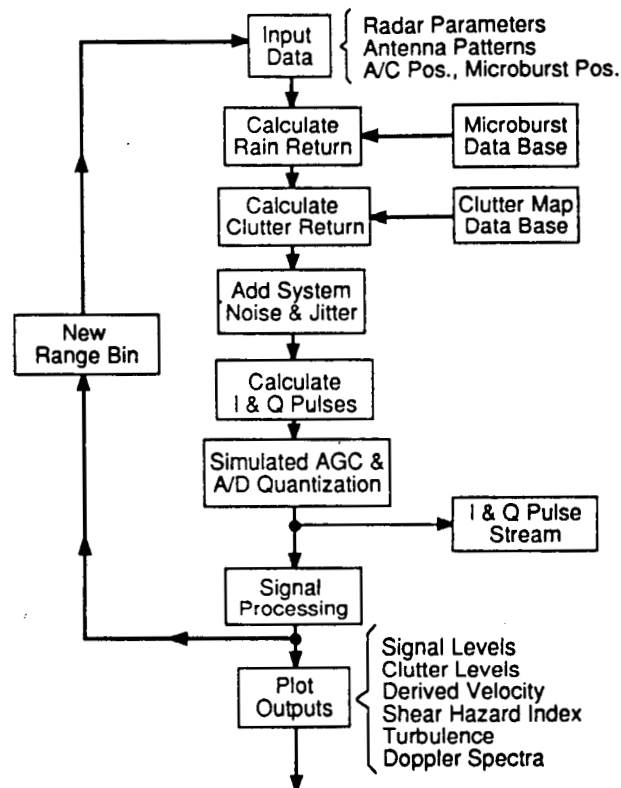


Fig. 8 Block diagram of the radar simulation program showing the major features of the simulation.

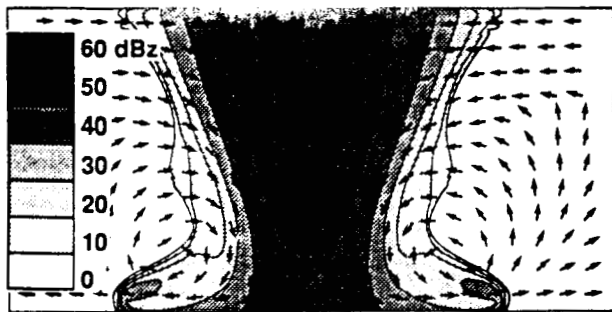


Fig. 9 Reflectivity contours and velocity field for the axisymmetric "wet" microburst model used for initial radar performance simulations studies.

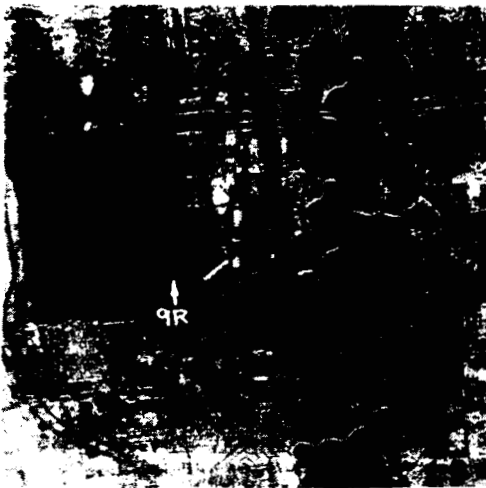


Fig. 10 High resolution SAR image of the Willow Run, MI airport area. NRCS map, produced from this image data base, is used to calculate the ground clutter return in the radar simulation program.

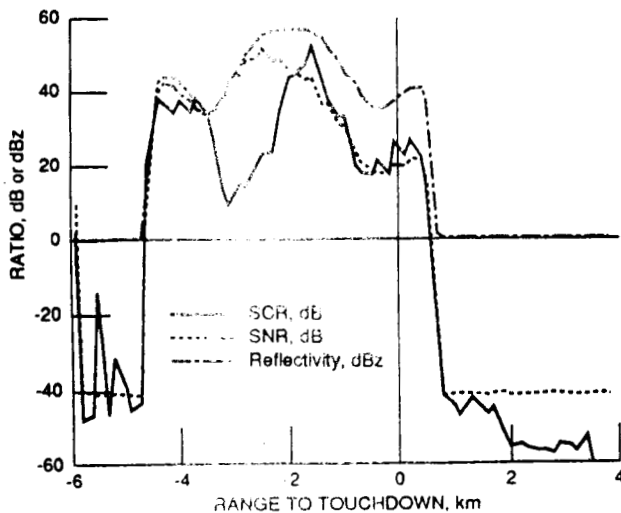


Fig. 11 Plot of calculated SNR, SCR and reflectivity factor vs range to touchdown for the "wet" microburst. Aircraft located -7km from touchdown on  $3^\circ$  glide slope, radar antenna tilt =  $2^\circ$ , microburst centered on projected flight path -2km from the touchdown point, freq. = 9.3 GHz.

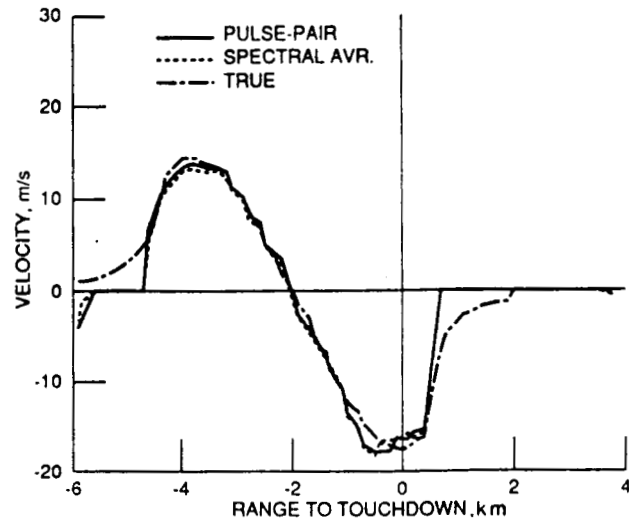


Fig. 12 Radar wind velocity measurement vs range to touchdown; same conditions as in figure 11. In this plot, positive velocities represent headwinds.

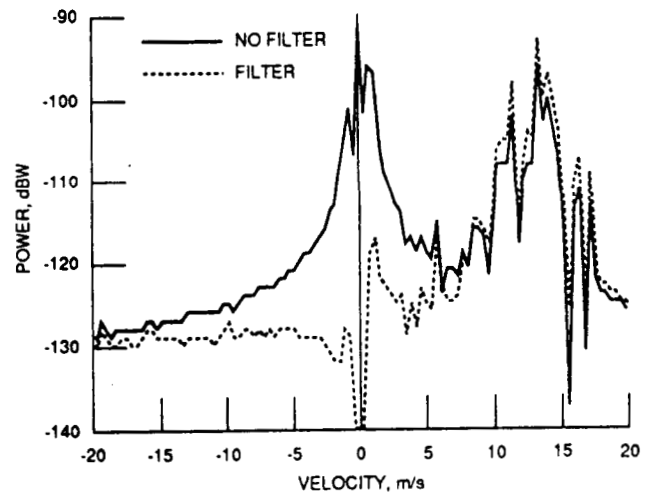


Fig. 13 Plot of Doppler spectrum from radar range bin 4km from touchdown, prior to wind velocity estimation, showing effect of 2-pole filter used to suppress ground clutter.

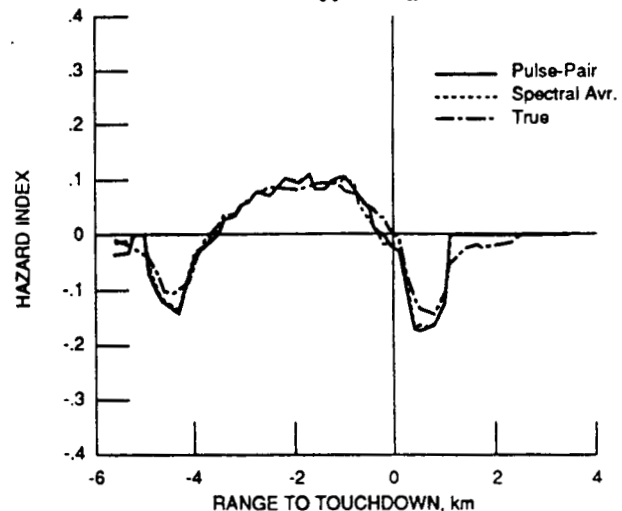


Fig. 14 Hazard index vs. range to touchdown derived from the velocities shown in figure 12. Index is calculated from average velocity differences over 5 range cells (750m).

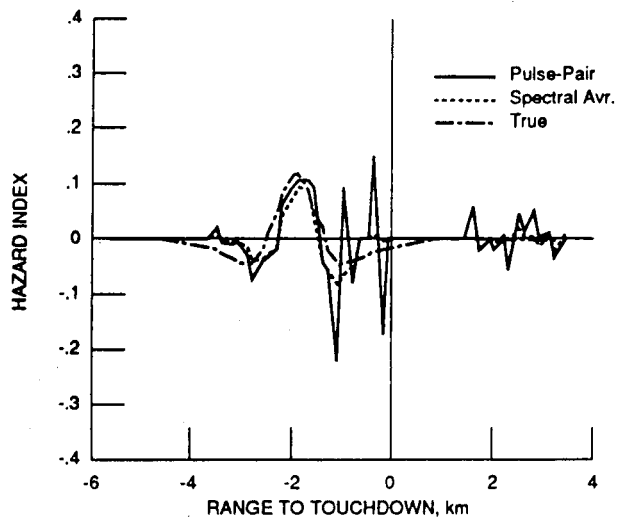


Fig. 15 Hazard index vs. range to touchdown derived from the "dry" microburst velocities using the baseline parameters, and conditions listed in fig. 11, freq. = 9.3 GHz.

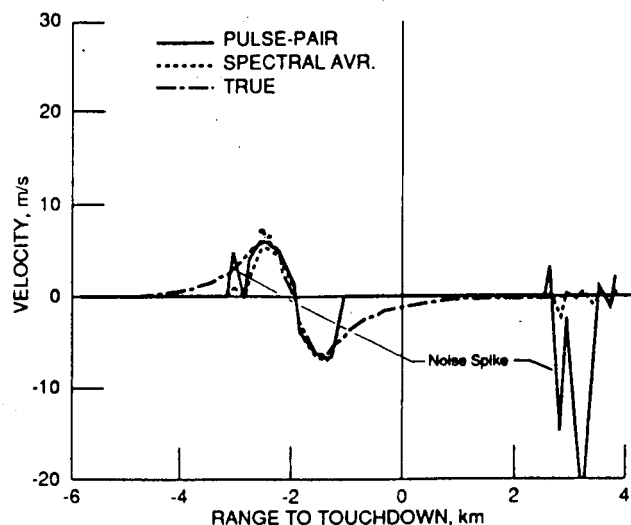


Fig. 17 Radar wind velocity measurement vs range to touchdown under same conditions as those of figure 16. The noise spikes are due to low SCR from urban clutter (-3km), and other clutter sources (+3km) where reflectivity levels are low.

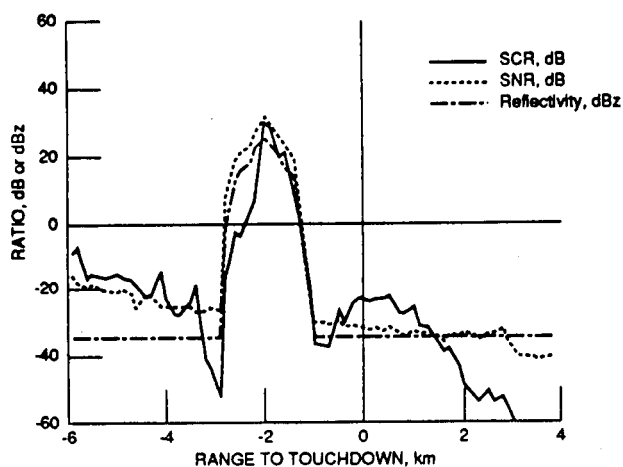


Fig. 16 Plot of calculated SNR, SCR and reflectivity factor vs range to touchdown for the "dry" microburst, and conditions listed in fig. 11, except freq. = 15 GHz.

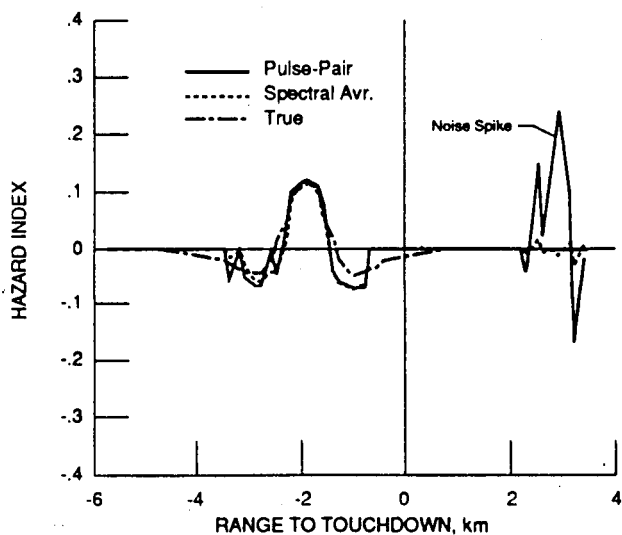


Fig. 18 Hazard index vs. range to touchdown derived from the "dry" microburst velocities shown in figure 17.

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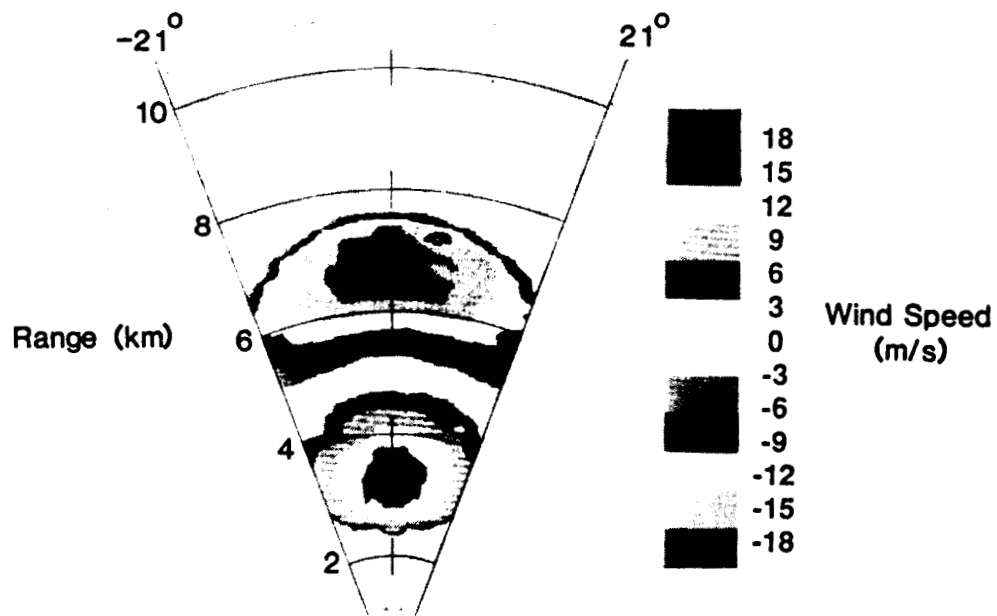


Fig. 19 Range-azimuth display of wind velocity contours for the "wet" microburst, baseline radar parameters, and conditions listed in fig. 11. The large head to tail velocity and wind direction change is clearly shown.

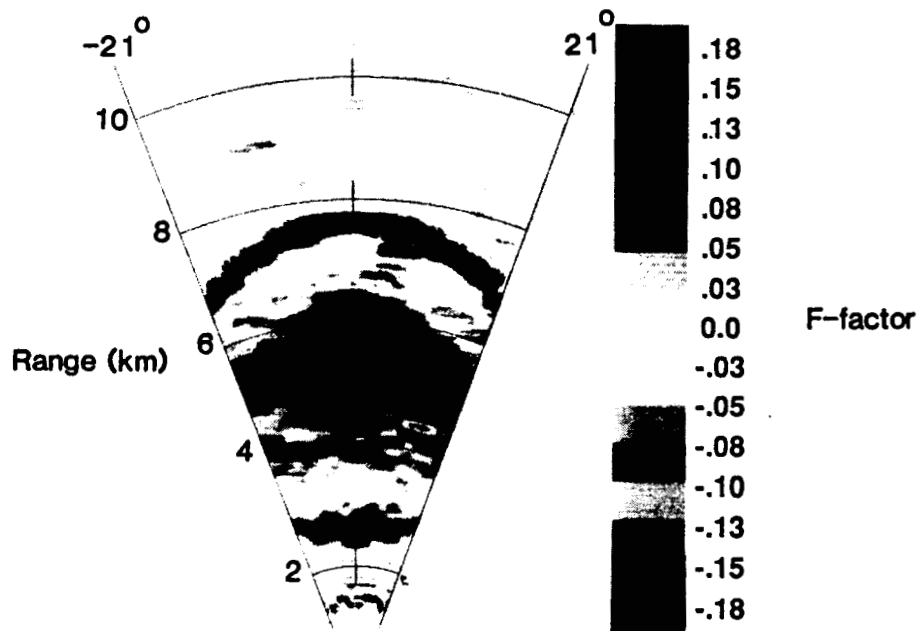


Fig. 20 Range-azimuth display of hazard index (F-factor) contours for the "wet" microburst, same conditions as fig. 19. The potential shear hazard area is clearly shown.

## **Session I. Airborne-Sensors**

**Analysis of Synthetic Aperture Radar (SAR) Data for Wind Shear Radar  
Clutter Modelling  
D. Gineris, ERIM  
S. Harrah, NASA LaRC  
V. Delnore, PRC**

# **ANALYSIS OF SYNTHETIC APERTURE RADAR (SAR) DATA FOR WINDSHEAR RADAR CLUTTER MODELLING**

**D. Gineris, ERIM  
S. Harrah, NASA  
V. Delnore, PRC**

## The NASA-~~ERIM~~ Contract

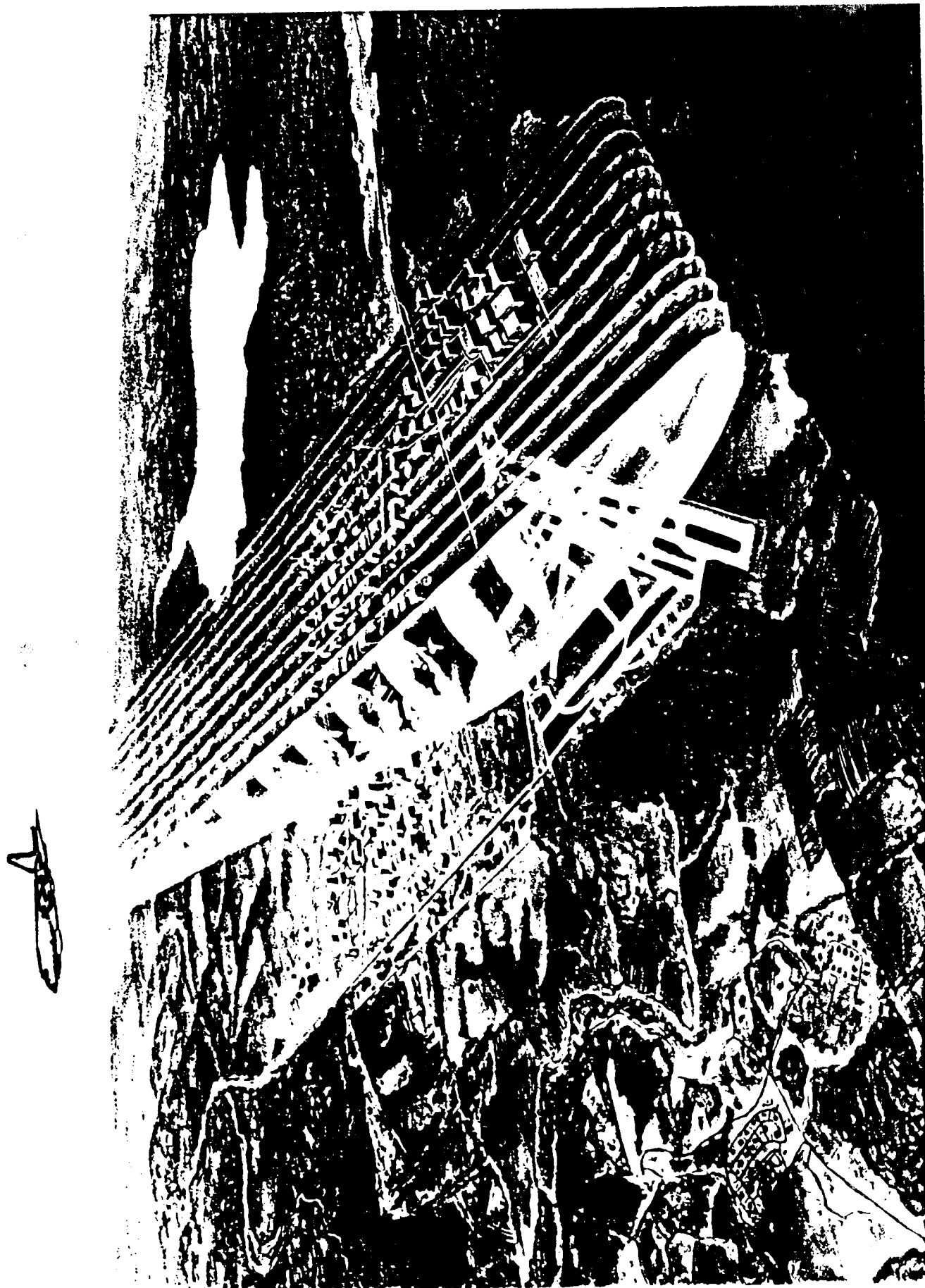
Φ1: Airport scenes from ERIM data base  
ERIM analysis  
NASA analysis

Φ2: Flights of opportunity

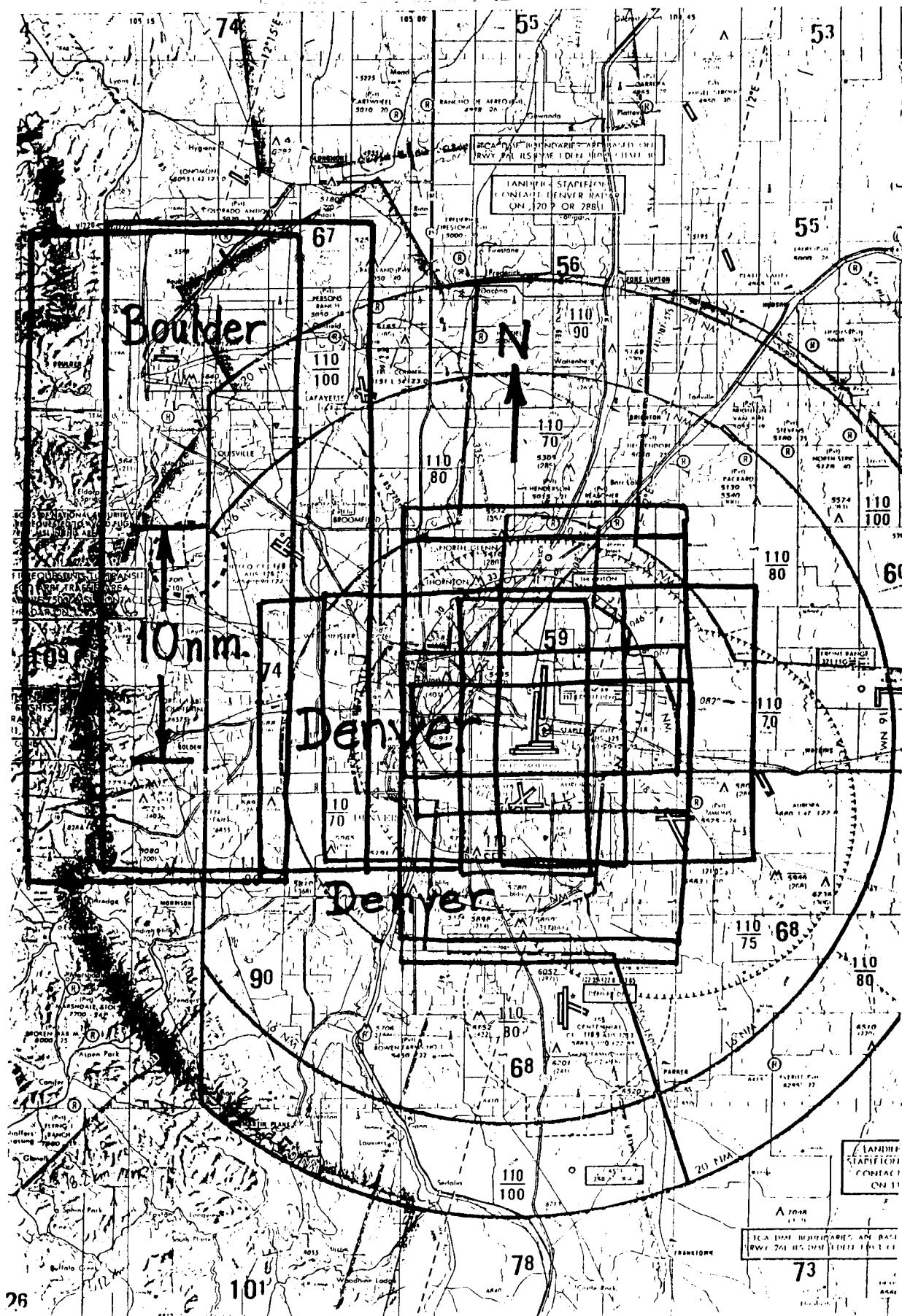
Φ3: Dedicated NASA flight

Some aspects from Φ1: the ERIM analysis

Willow Run Airport statistics







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# Selected NASA Images

NASA LaRC Image #	Date	Pass	Scene	Polarization	Depression Angle (°)	Incidence Angle Range (°)	Aircraft Flight Direction	Radar Look Direction
1	17 December 1984	4	Willow Run Airport Ypsilanti, Michigan	VV	22	45 to 73	South- bound	Left (East)
2	7 April 1984	4	Willow Run Airport Ypsilanti, Michigan	HH	28	36 to 64	North- bound	Right (East)
3	2 August 1984	4	Ottawa International Airport Ottawa, Canada	HH	24	39 to 64	South Southeast	Right (WSW)
4	3 August 1983	7	Comox CFB British Columbia, Canada	VV	42	12 to 58	Northeast	Left (NW)
5	7 April 1984	3	Willow Run Airport Ypsilanti, Michigan	VV	28	33 to 63	North- bound	Right (East)
6	25 July 1983	1	Victoria International Airport British Columbia, Canada	VV	40	25 to 60	North- bound	Left (West)
7	7 September 1984	1	Peconic River Airport Long Island, N.Y.	HH	15	43 to 72	Northwest	Right (NE)
8	26 July 1983	2	Victoria International Airport British Columbia, Canada	HH	40	16 to 60	South- bound	Right (West)
9	4 September 1984	1	Hampton County Airport Long Island, N.Y.	HH	28	0 to 58	Northwest	Right (NE)

# Analysis of Specific Areas

## Input:

- specific areas in the image which can be classified are located and extracted from the image

## Process:

- statistical analysis of each image 'dump' are performed. This analysis calculates the mean, skew, and kurtosis of the 'dumped' area. A probability density function is fit to the data.

## Output:

- statistical summaries of each particular clutter group in the image.
- bar charts of the statistical data
- histograms of each type of clutter group in the image

# SAR IMAGE 2

## WILLOW RUN AIRPORT

- |                       |                    |                   |                    |
|-----------------------|--------------------|-------------------|--------------------|
| 1,2,3,4,5 Light Poles | 13 Bridge          | 29 Edge of Hangar | 34,35 Parking Lots |
| 7,8,9,10,11 Lake Sfc. | 14,15 Riverbank    | 30 Airport bldgs  | 38 Forest          |
| 12 Apt. Complex       | 22,24 Grass Fields | 31 Large Factory  | 38' Residential    |
|                       | 25,26,27 Runway    | 32,33 Hangar      |                    |



(dB)

About 5 miles

Depr. angle

V

64.26°

(H)

(DEG)

inc

36.54°

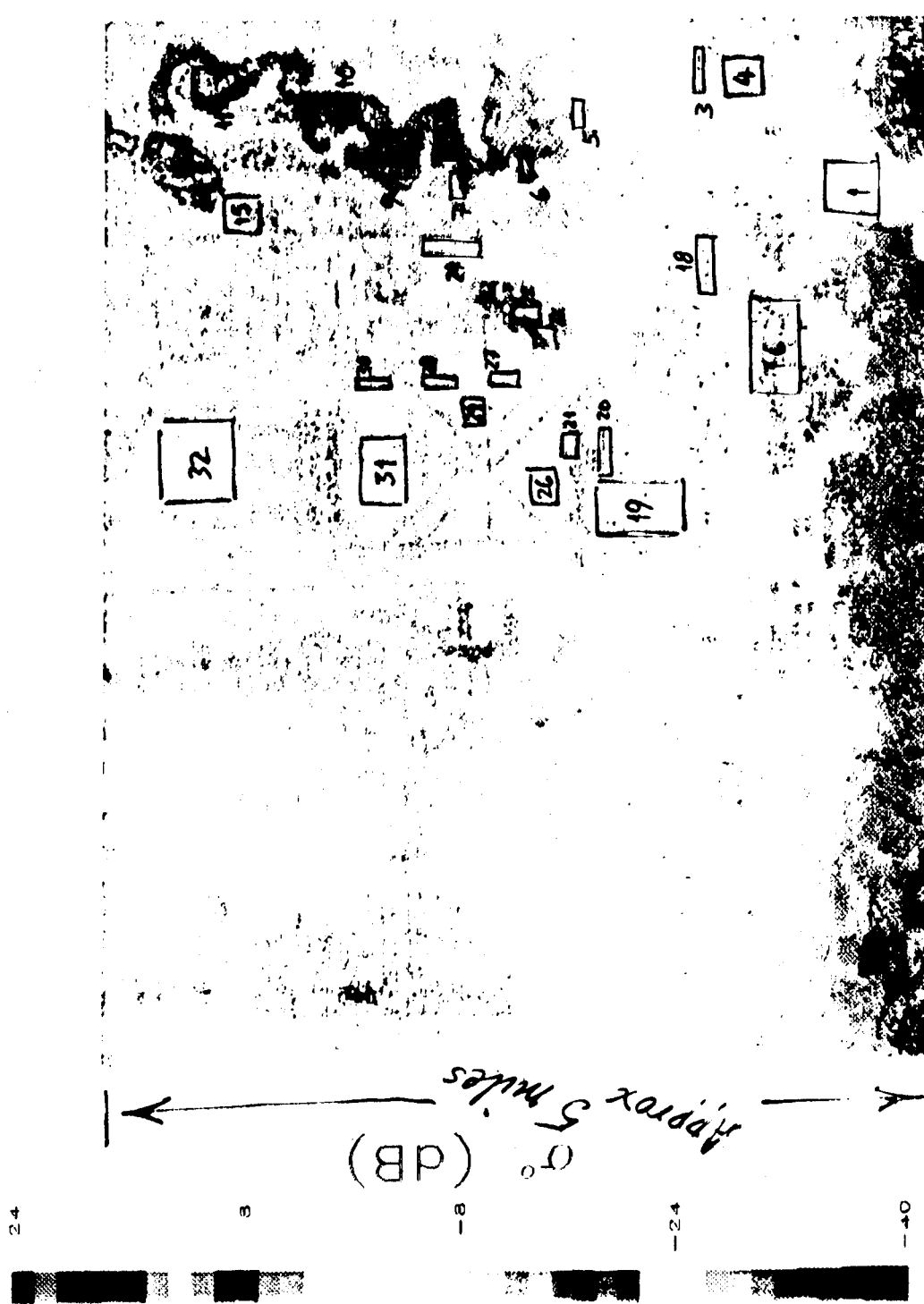
111 Doc., April 84

# SAR IMAGE 5 WILLOW RUN AIRPORT

*Dep. angle*  
 $64.26^\circ$

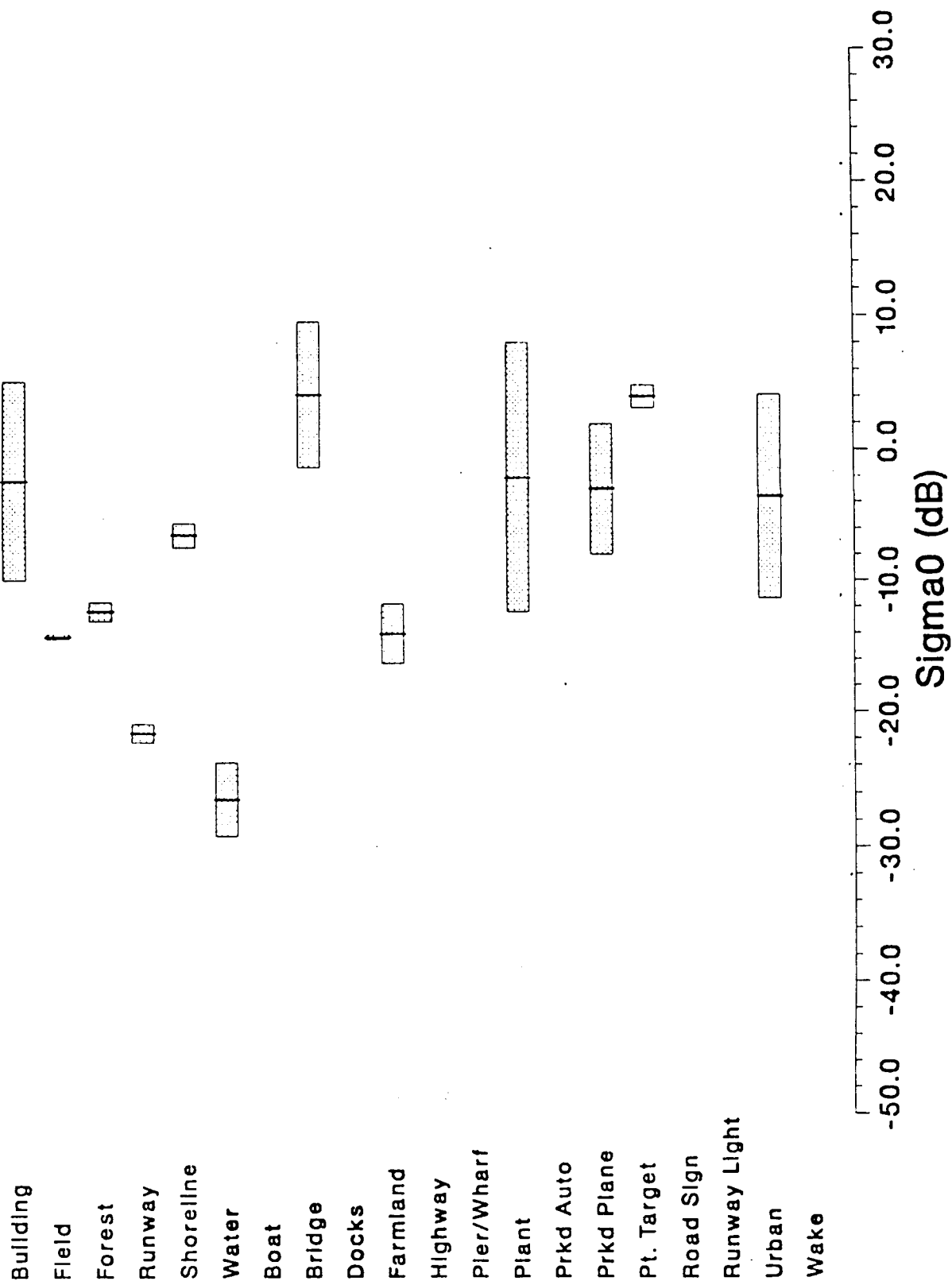
(H) (DEG)  
 inc

36. 540

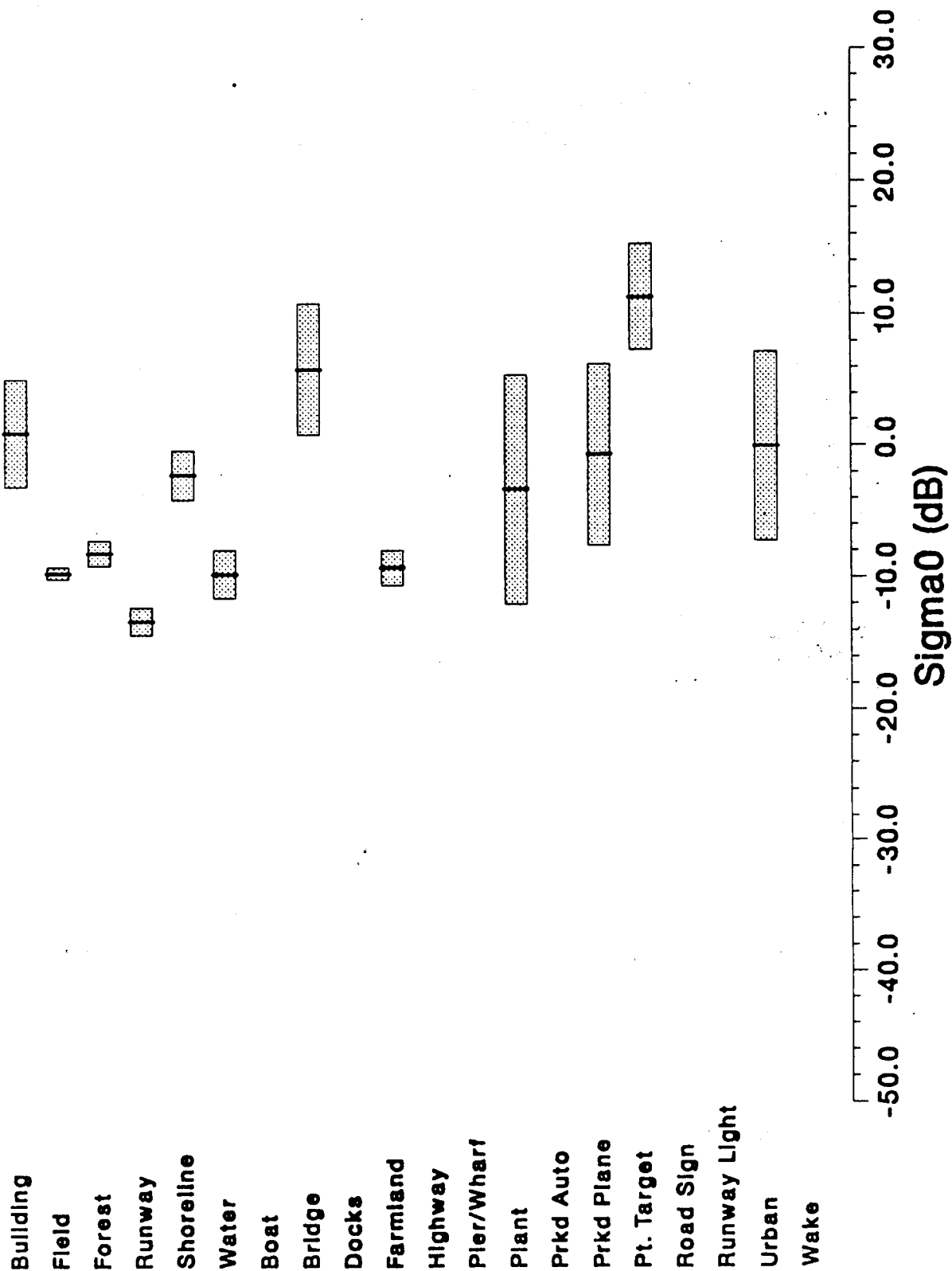


*11' Dec., April 84*

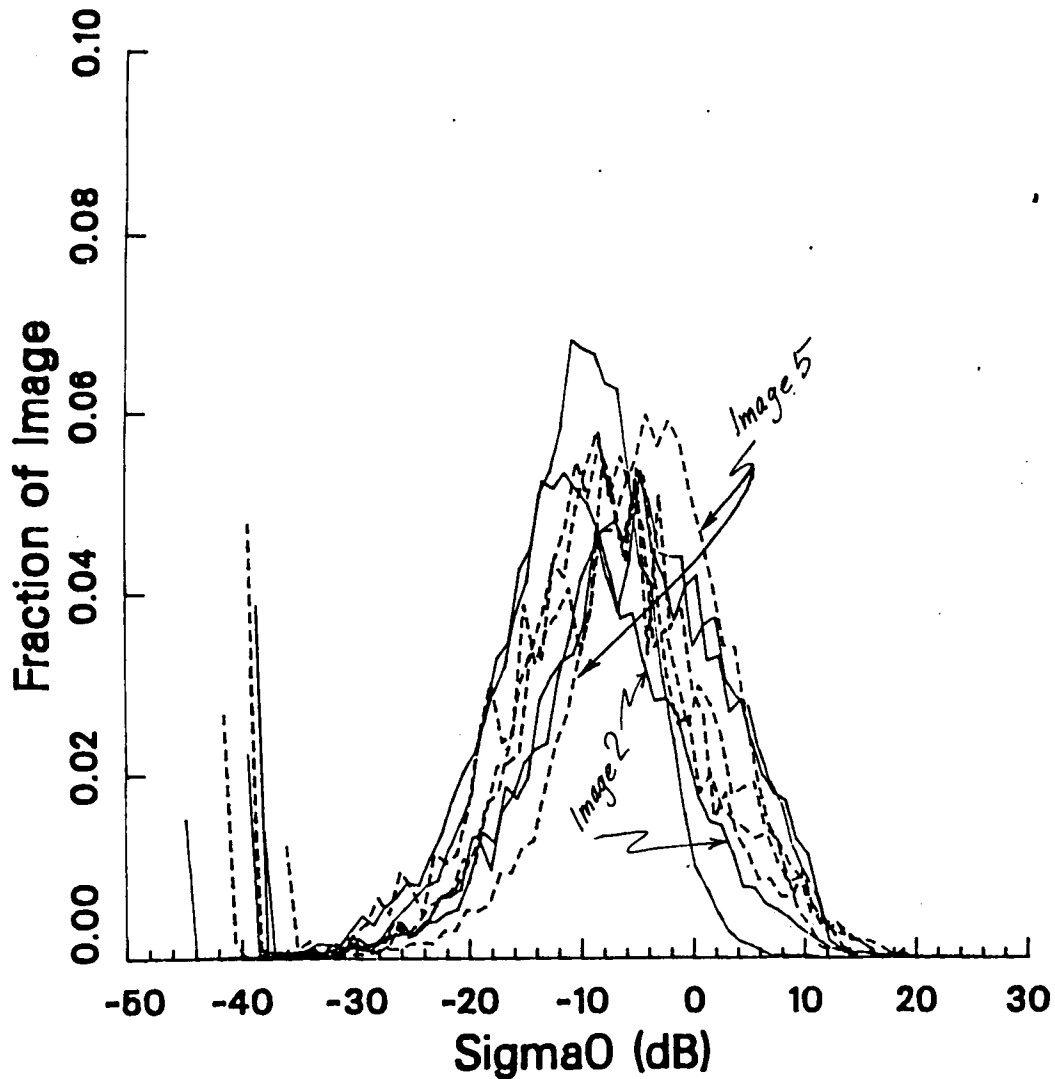
# STATISTICAL SUMMARY IMAGE2 - X944



# STATISTICAL SUMMARY IMAGE5 - X1404



## Probability Density Function of Building Clutter Areas



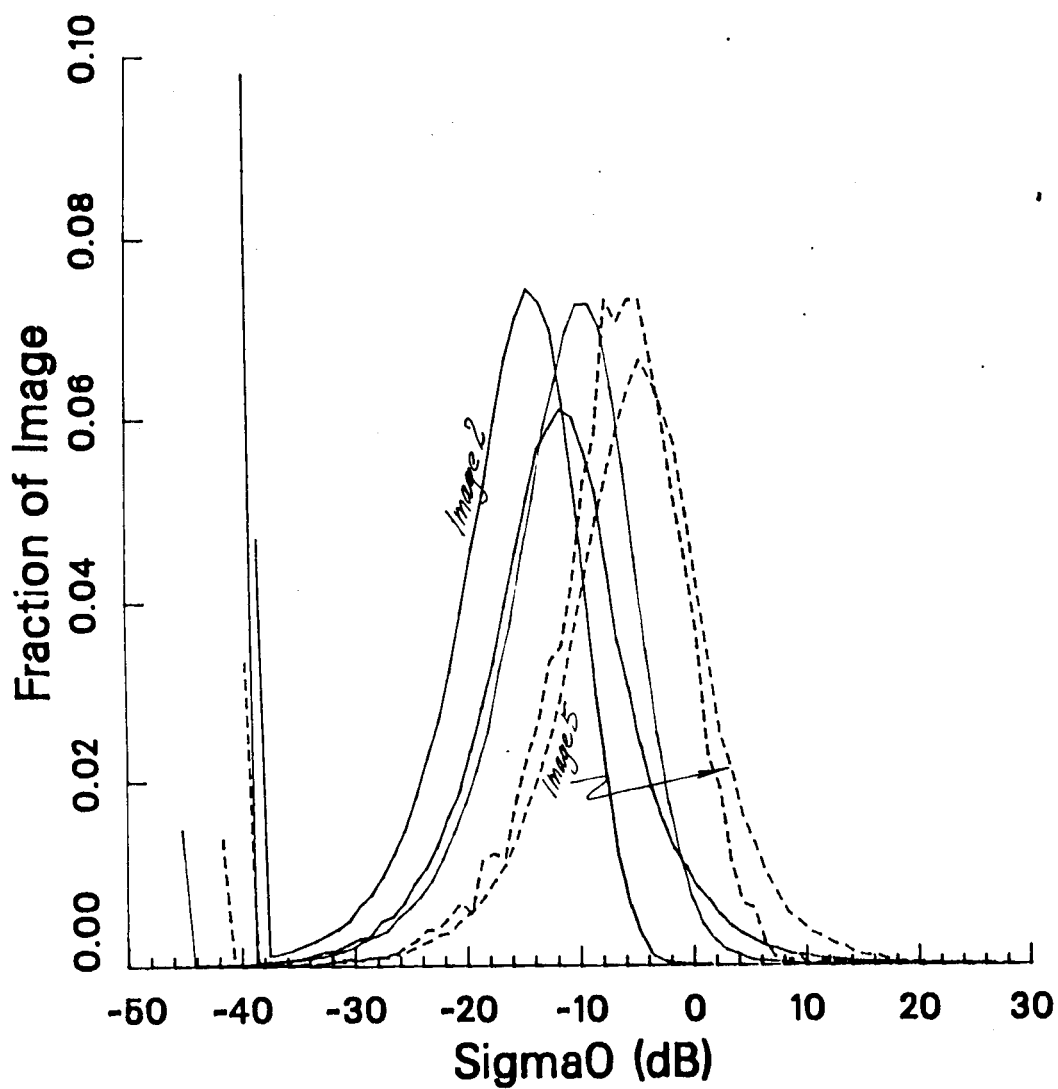
Minimum: -45.81

Maximum: 24.01

LEGEND	
Image 1	---
Image 2	---
Image 3	---
Image 4	---
Image 5	---
Image 6	---
Image 7	---
Image 8	---



## Probability Density Function of Urban Clutter Areas



Minimum: -46.14

Maximum: 27.22

### LEGEND

- Image 1
- Image 2
- Image 3
- Image 5
- Image 8

## Threshold Bin Values

Image #	Date	below -10 dB	-10 to -5 dB	-5 to 0 dB	0 to 5 dB	5 to 10 dB	above 10 dB
1	17 December 1984	52.76%	32.98%	13.00%	1.13%	0.12%	0.004%
2	7 April 1984	69.25%	24.58%	4.72%	1.21%	0.23%	0.02%
3	2 August 1984	40.69%	24.80%	32.42%	1.78%	0.29%	0.03%
4	3 August 1983	44.80%	37.73%	12.00%	5.27%	0.23%	0.002%
5	7 April 1984	7.70%	41.75%	29.41%	13.26%	6.49%	1.38%
6	25 July 1983	32.15%	56.28%	10.06%	1.49%	0.01%	0.00%
7	7 September 1984	69.05%	18.66%	11.99%	0.29%	0.01%	0.00%
8	26 July 1983	51.04%	21.37%	12.18%	14.03%	1.37%	0.00%

## **Results of Inter-Image Analysis**

- similar clutter areas in all images have similar clutter characteristics; mean values may change from image to image because of differences in incidence angle, but the probability density functions which describe a particular type of clutter are similar from image to image.
- point target clutter does not seem to change over the range of incidence angles present in the images.

# Results of Intra-Image Analysis

- the majority of the clutter areas with returns greater than -5 dB are located around the airports and in near range. Roughly 2% to 3% of the image has returns greater than 0 dB. The areas of lowest return (other than water) are also located at the airport.
- distributed targets such as forests, fields, runways, and urban areas rarely have a mean  $\sigma^0$  greater than -5 dB.
- urban areas and forested areas have similar clutter characteristics. The percentage of point targets in an urban area is only about 5% to 10% of the total area.

## **Session I. Airborne—Sensors**

**Preliminary Airborne Wind Shear Detection Radar Assessment Study**  
**C. L. Britt, RTI**  
**E. M. Bracalente, NASA LaRC**

# ***PRELIMINARY AIRBORNE WIND SHEAR DETECTION RADAR ASSESSMENT STUDY***

Charles L. Britt, Ph.D.  
Research Triangle Institute

&

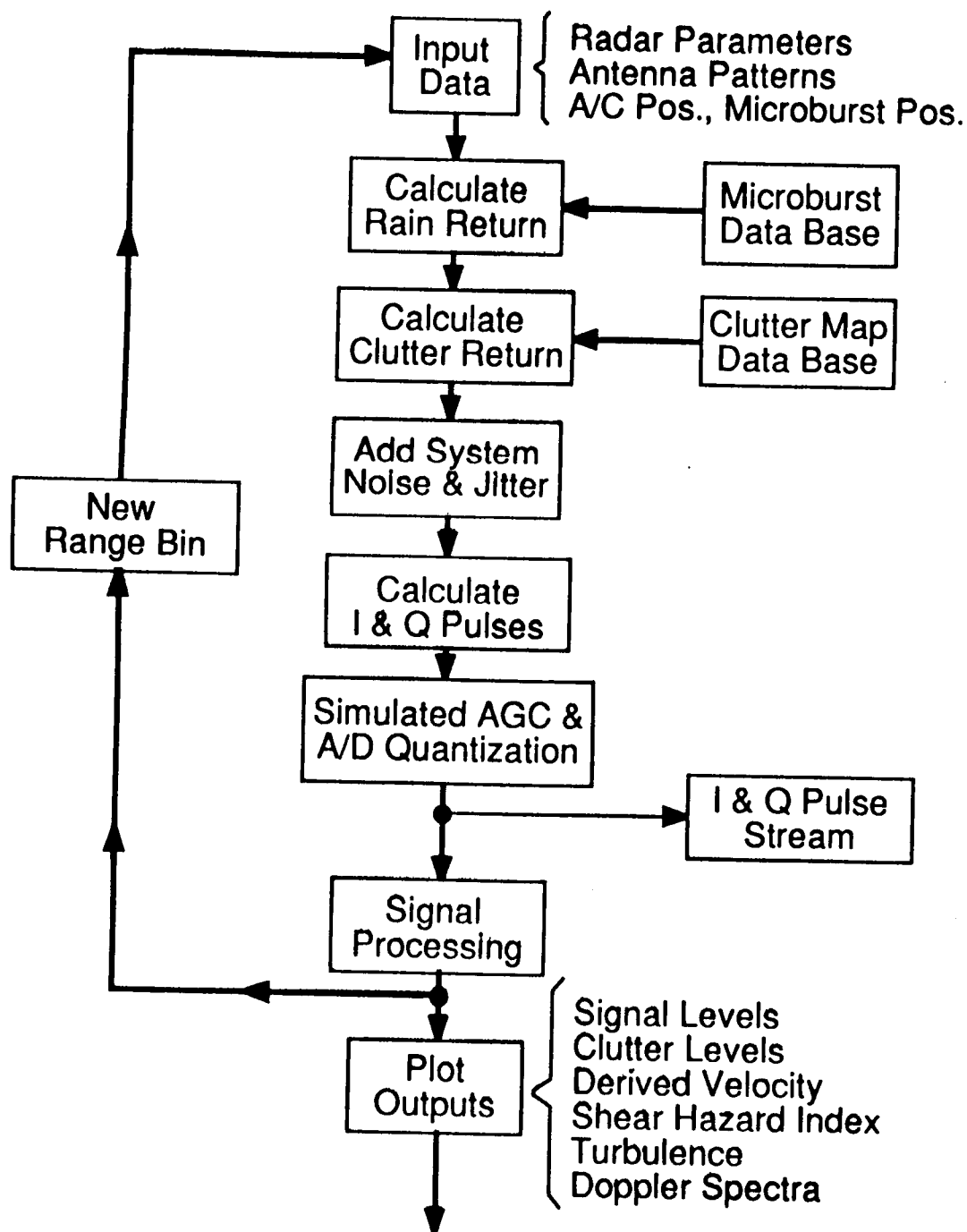
Emidio Bracalente  
NASA

# AIRBORNE DOPPLER RADAR DETECTION OF MICROBURST WINDSHEAR



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# RADAR SIMULATION

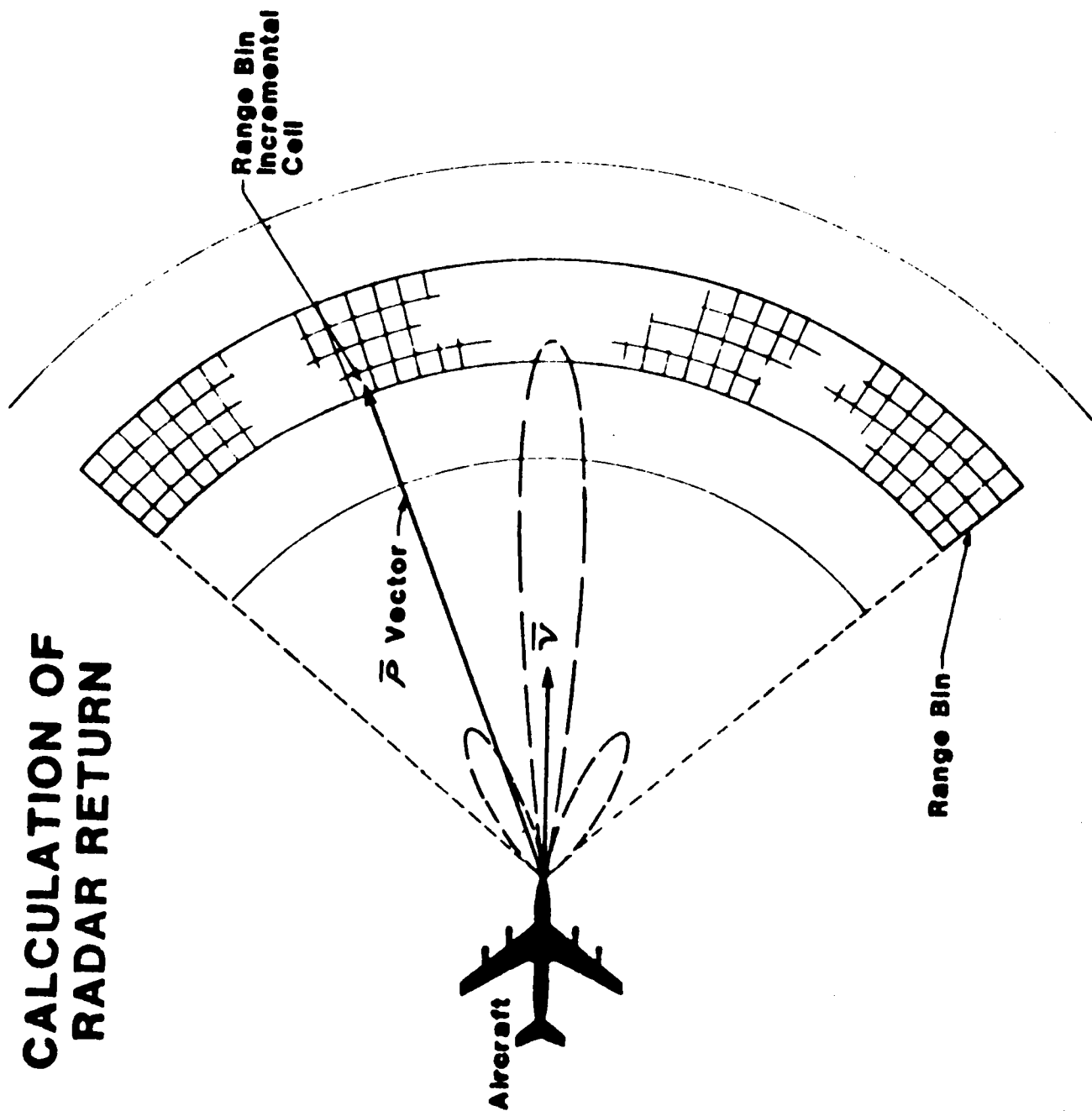




# ***BASELINE PARAMETERS***

Frequency	-----	9.3 GHz
Power	-----	2.0 KW
Pulse Width	-----	1.0 $\mu$ sec
P.R.F.	-----	3030 per sec
Antenna Dia.	-----	.76 meters
# of Pulses	-----	128
Processing	-----	Pulse-pair

# CALCULATION OF RADAR RETURN



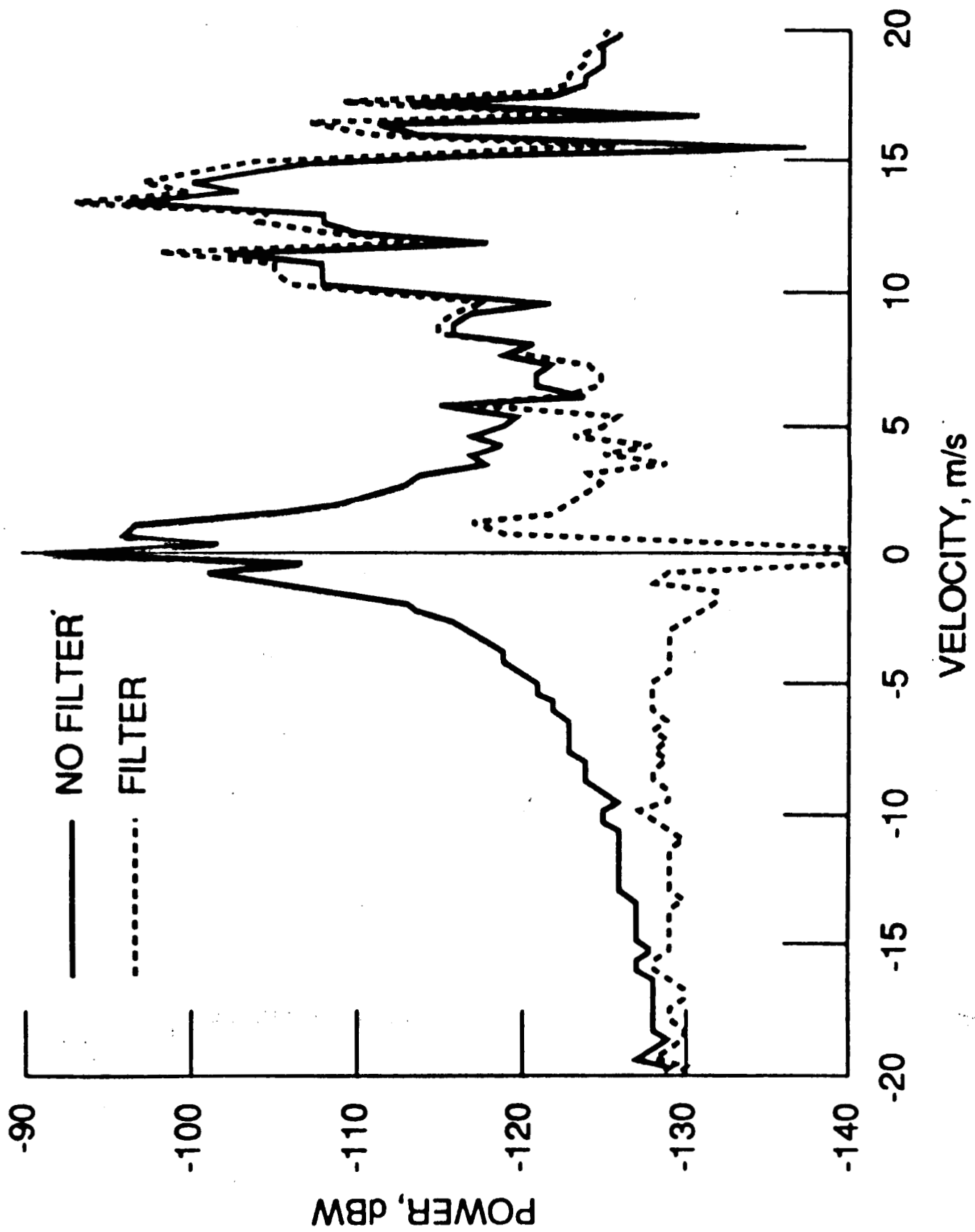
## CALCULATION OF I & Q

$$I(T) = \sum_{i=1}^N A_i \cos \left[ \phi_i + \beta (V_i - V_a) T + \Delta\phi \right] + \tilde{n}(T)$$

Amplitude of return from scatterer  $i$  →  $A_i$   
 Random phase of scatterer  $i$  →  $\phi_i$   
 Radial velocity component of scatterer  $i$  →  $V_i$   
 Radial component of A/C velocity →  $V_a$   
 Transmitter phase error →  $\Delta\phi$   
 Receiver noise →  $\tilde{n}(T)$

$$\beta = \frac{2\pi}{\lambda_0}$$

T = Time



780507001007

# HAZARD INDEX

$$F = \frac{\dot{W}_x}{g} - \frac{W_h}{V}$$

Radial      Vertical  
Component   Component

LET:

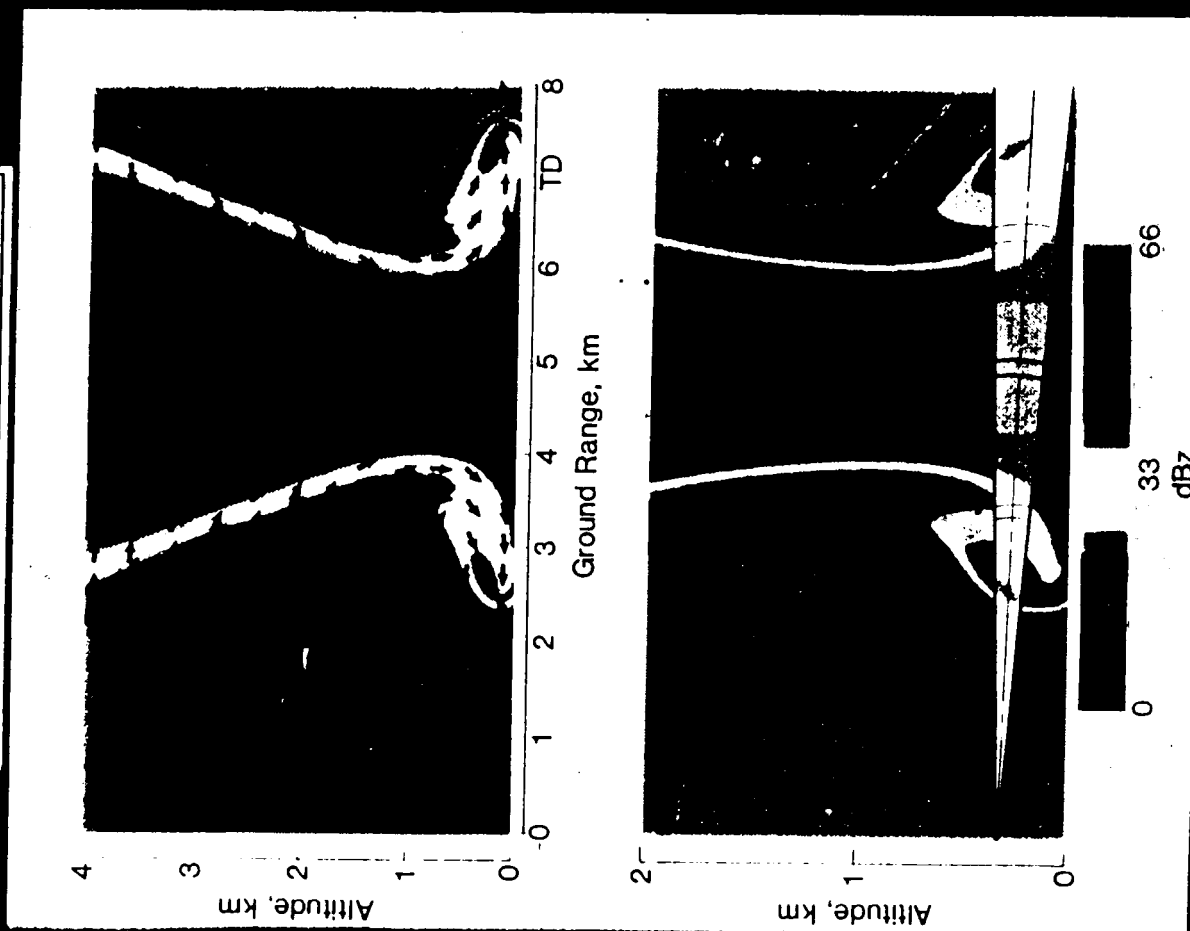
$$\dot{W}_x = V \frac{\delta W_x}{\delta R}$$

THEN:

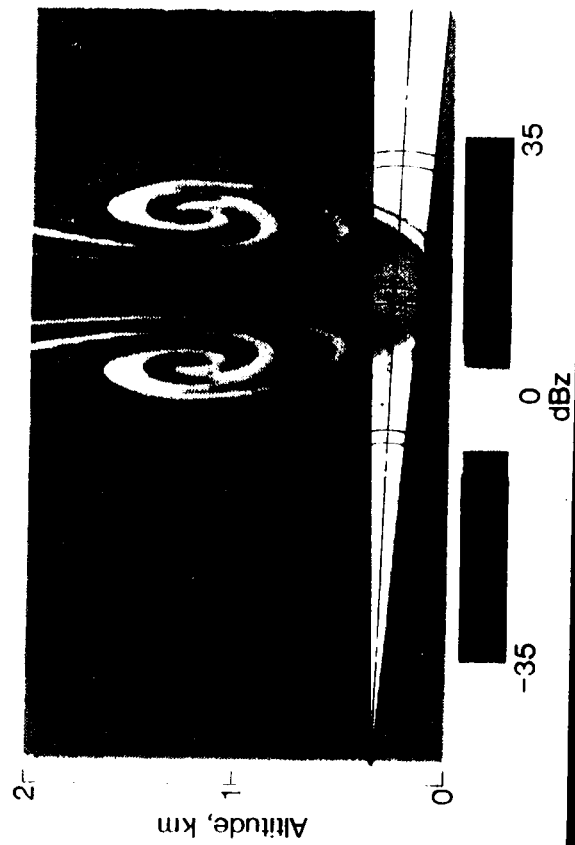
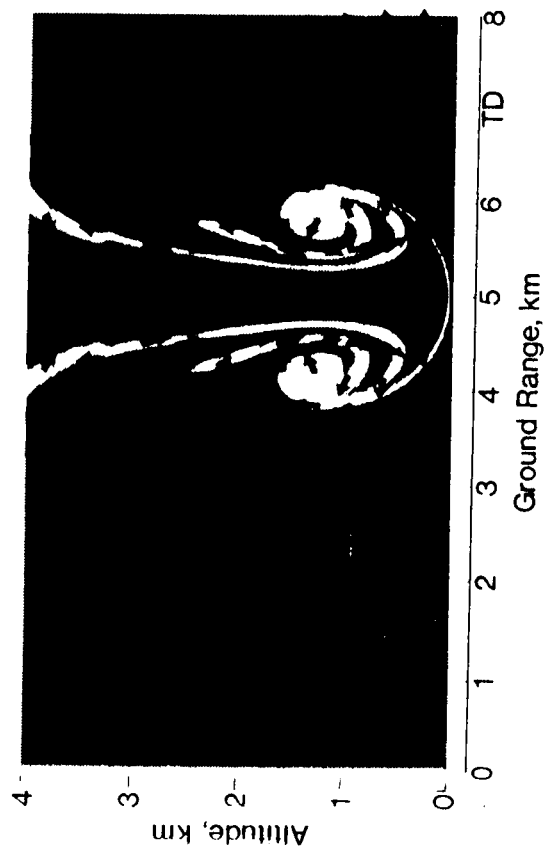
$$F_{RAD.} = \frac{V}{g} \frac{\delta W_x}{\delta R}$$

$$= \frac{V}{g} \cdot \frac{(\text{Radial Velocity Change})}{(\text{Distance Between Range Bins})}$$

# WET MICROBURST



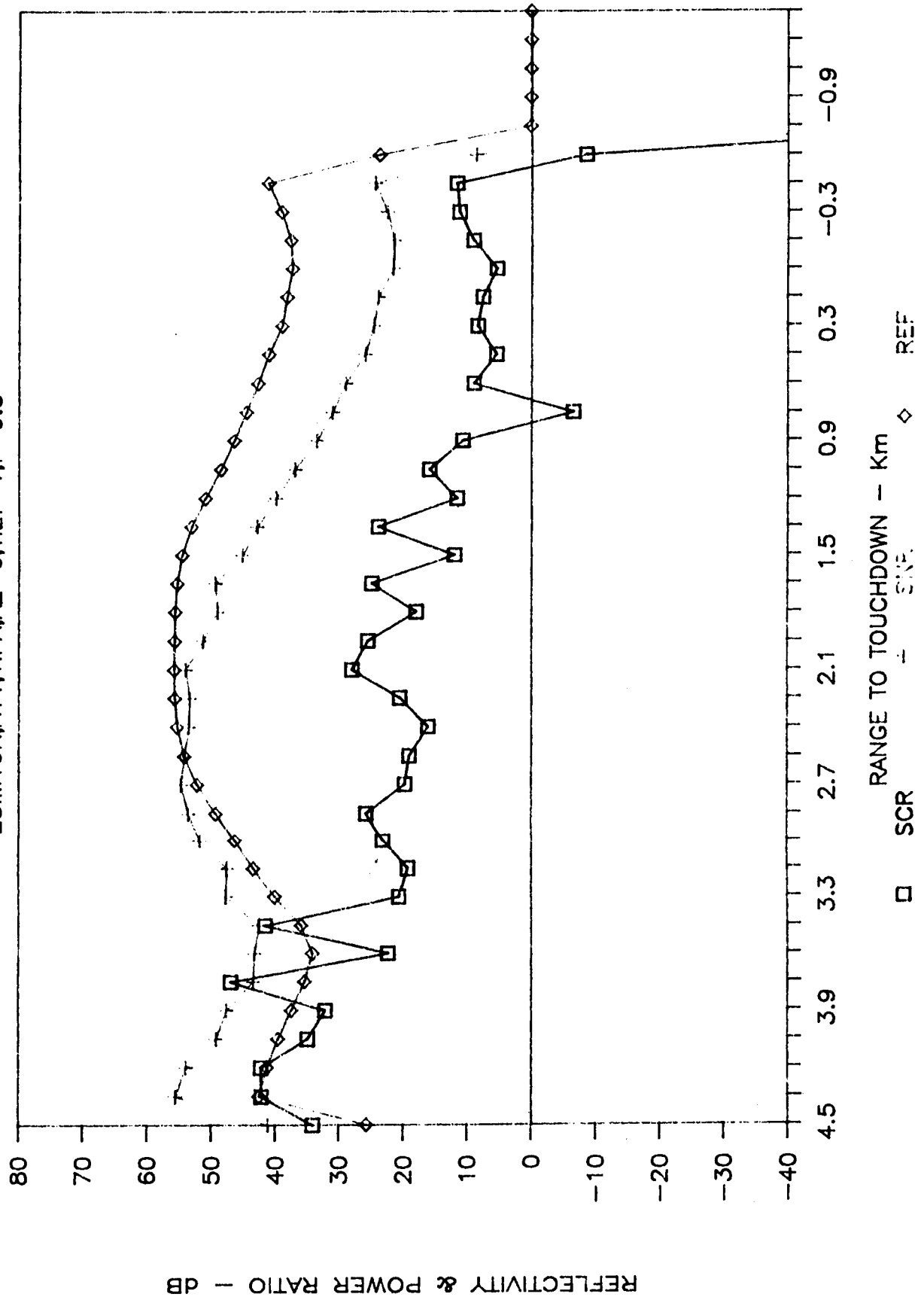
## DRY MICROBURST



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# SCR, SNR & REF

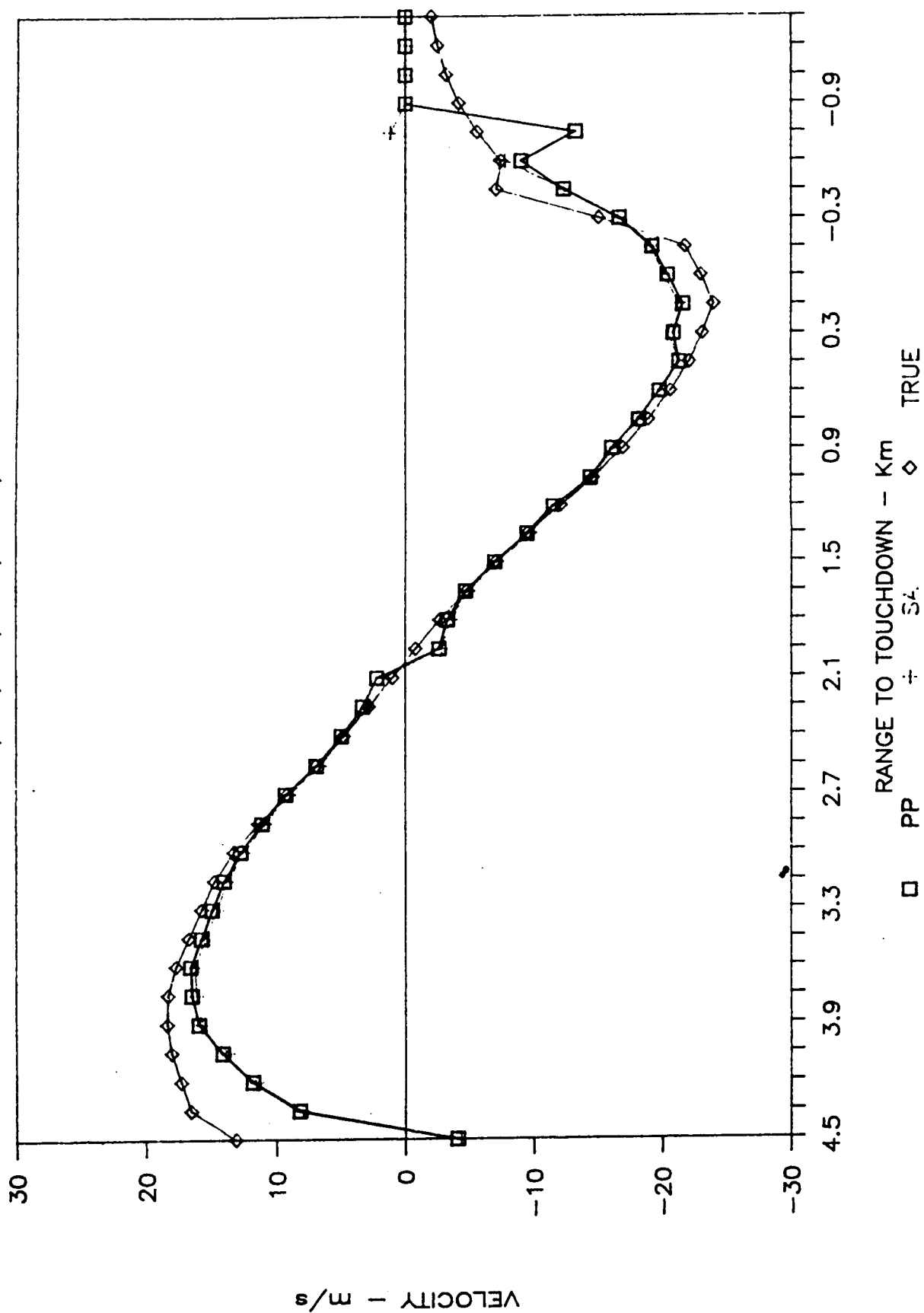
2SIM10R,A11,YPA,AZ=0,TILT=1,F=9.3





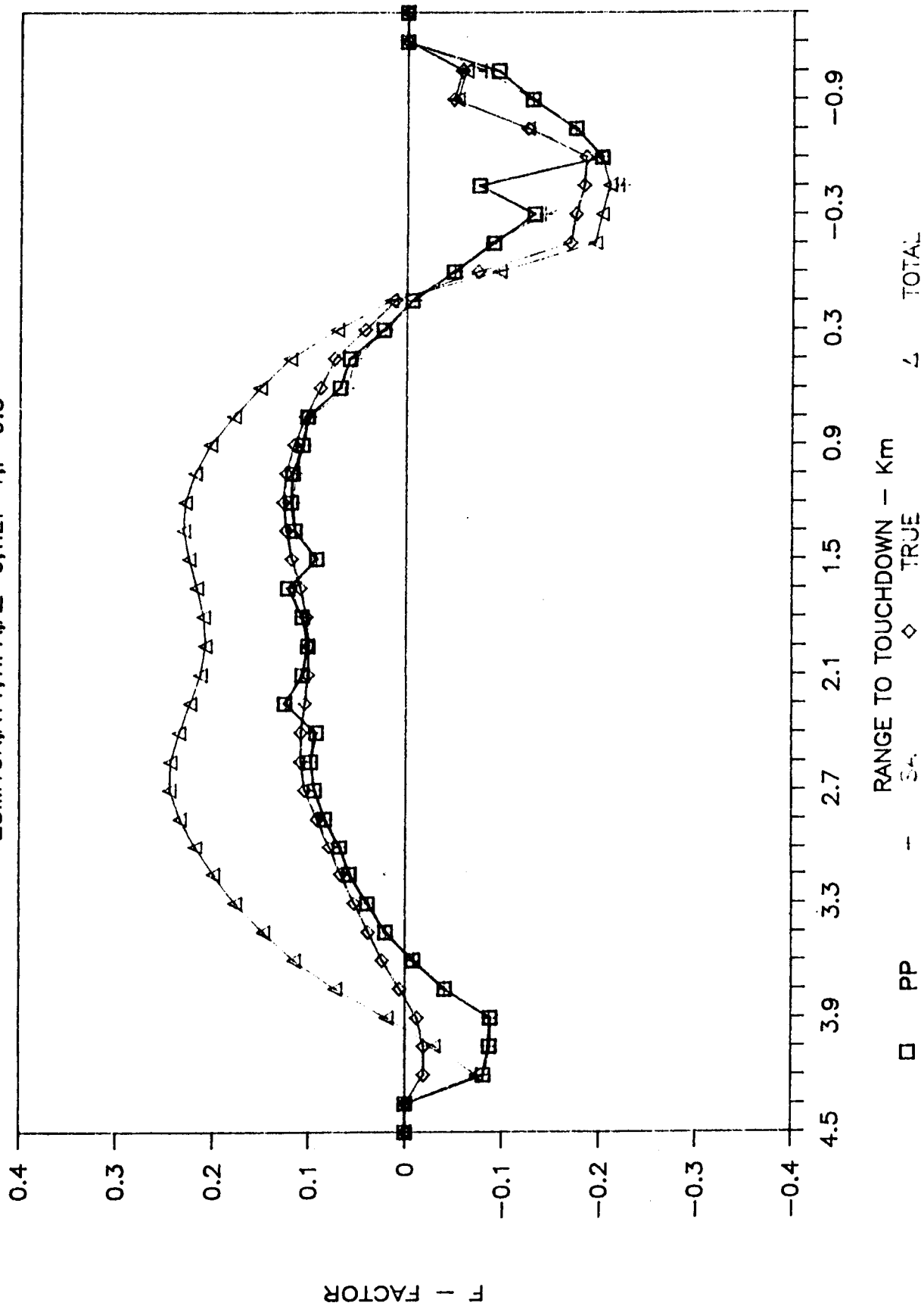
# MEASURED WIND VELOCITY - m/s

2SIM10R,A11,YIPA,AZ=0,TILT=1,F=9.3



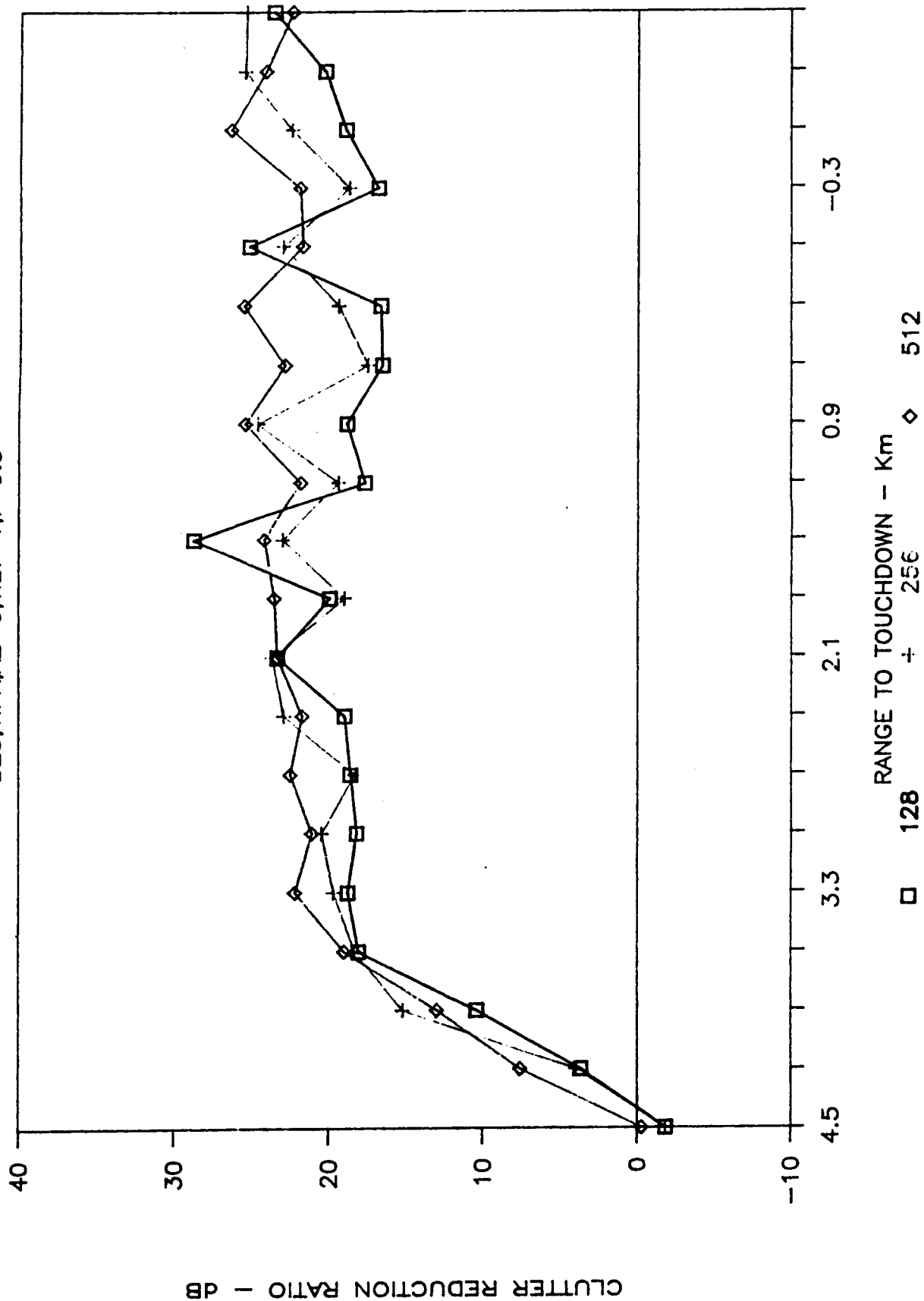
# HAZARD FACTOR VS. RANGE

2SIM10R,A11,YPA,AZ=0,TILT=1,F=9.3

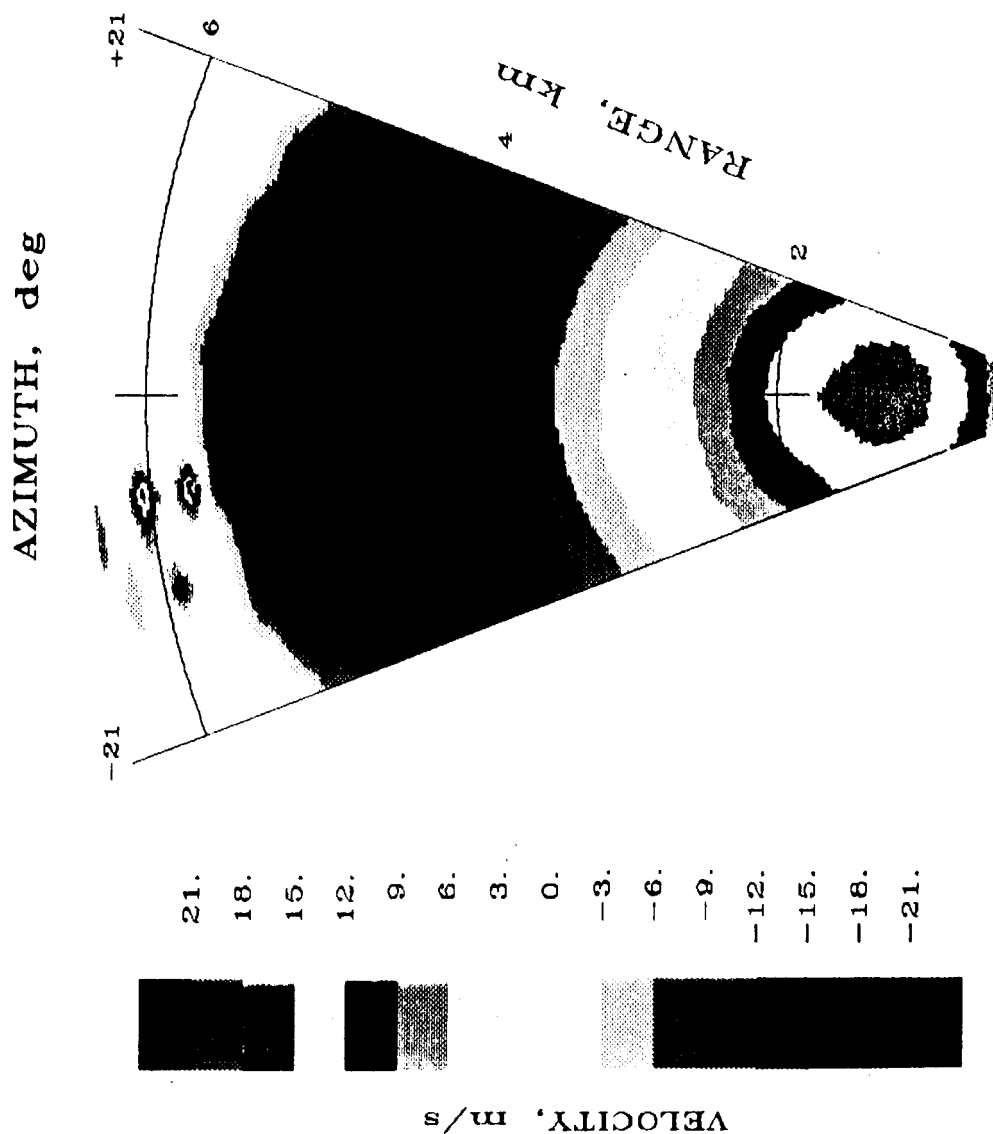


# CLUTTER SUPPRESSION

B23,YIPA,AZ=0,TILT=1,F=9.3

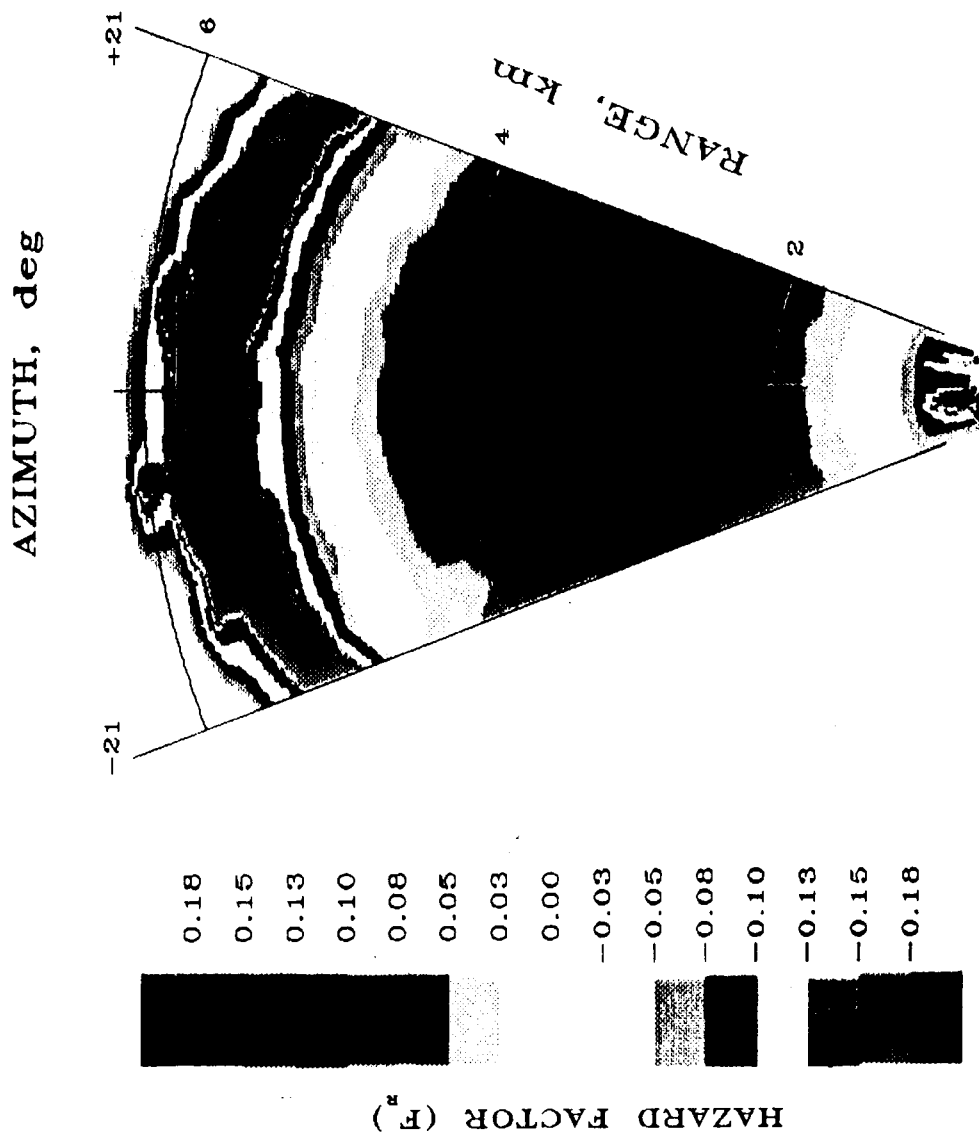


# WINDSHEAR RADAR VELOCITY



2SIM10SC WET MICROBURST A11 A/C RANGE=6 km TILT=1 deg  
FREQ=9.3 GHz

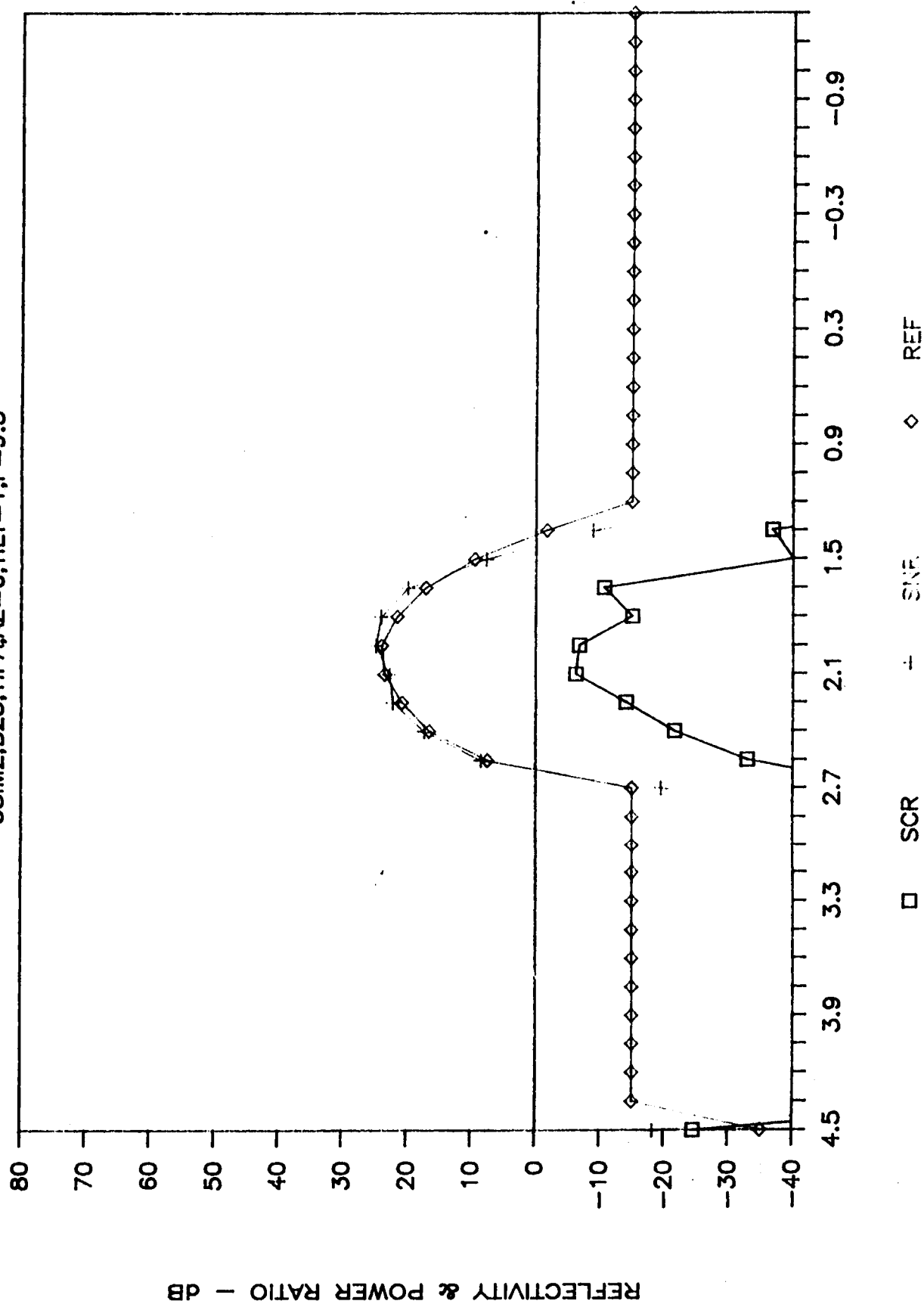
# WINDSHEAR RADAR HAZARD INDEX



2SIM10SC WET MICROBURST A11 A/C RANGE=5 km TILT=1 deg  
FREQ=9.3 GHz

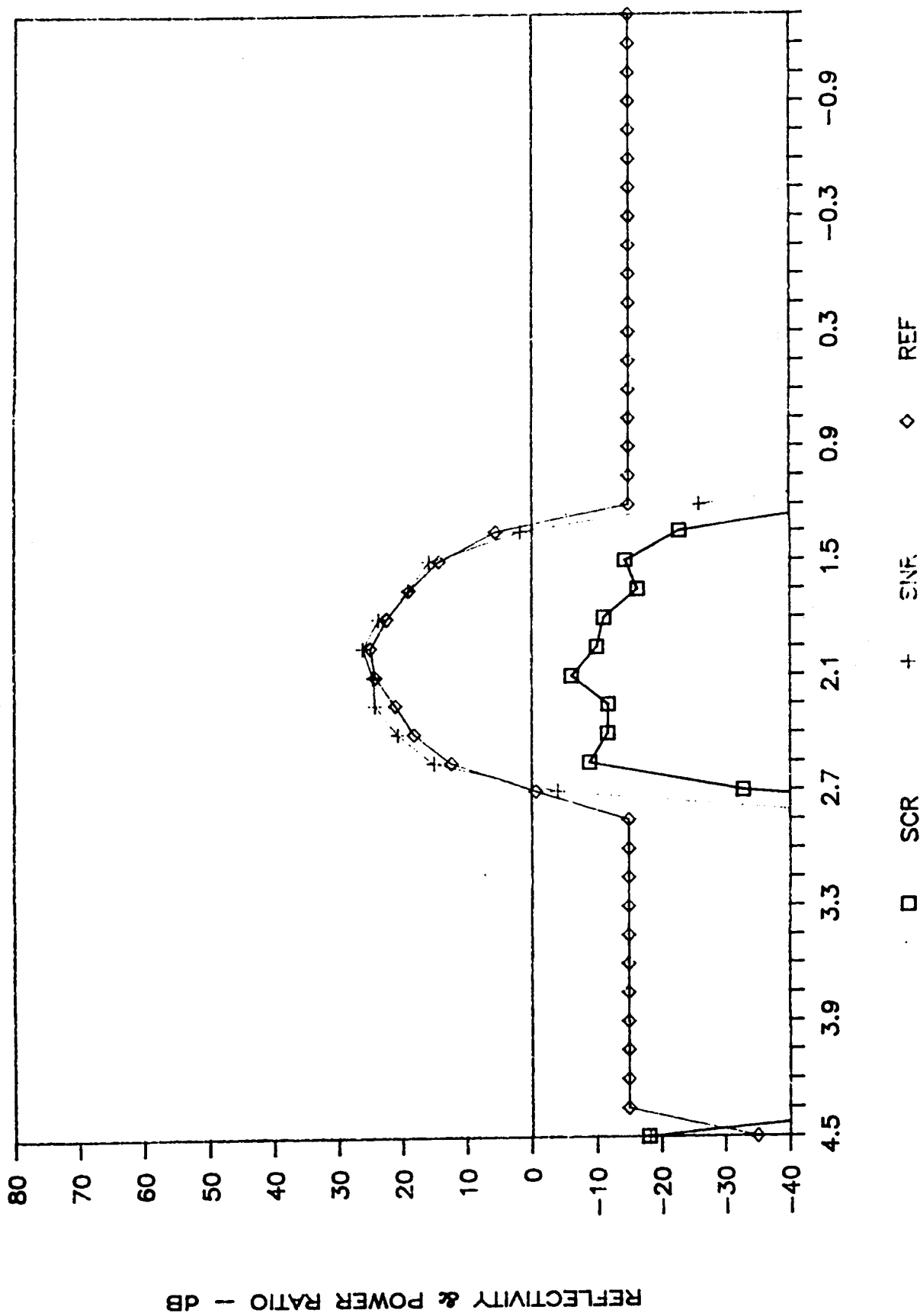
# SCR, SNR & REF

3SIM2,B23,YIP,AZ=0,TILT=1,F=9.3



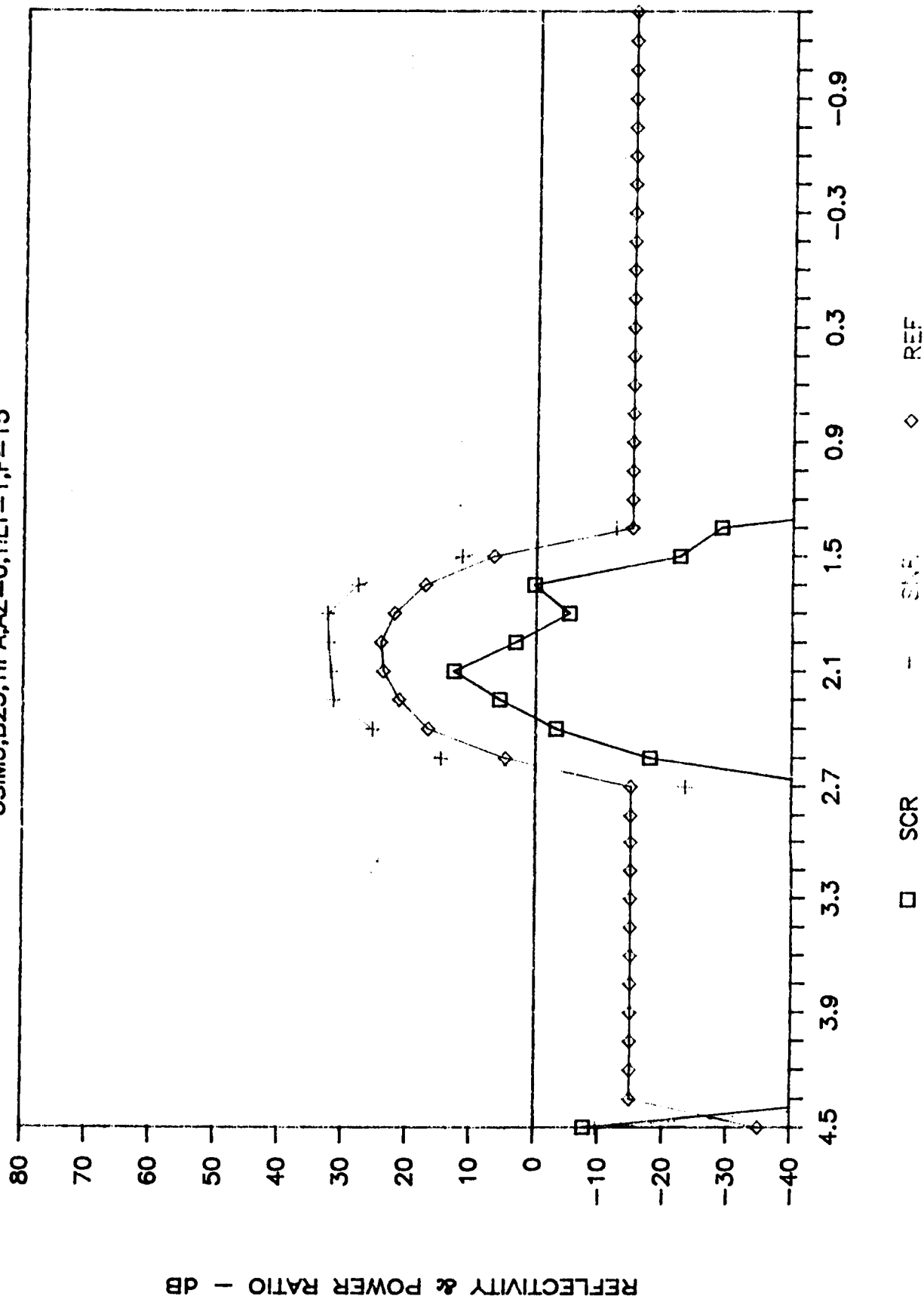
# SCR, SNR & REF

4SIM2,B23,YIPA,AZ=0,TILT=2,F=9.3



# SCR, SNR & REF

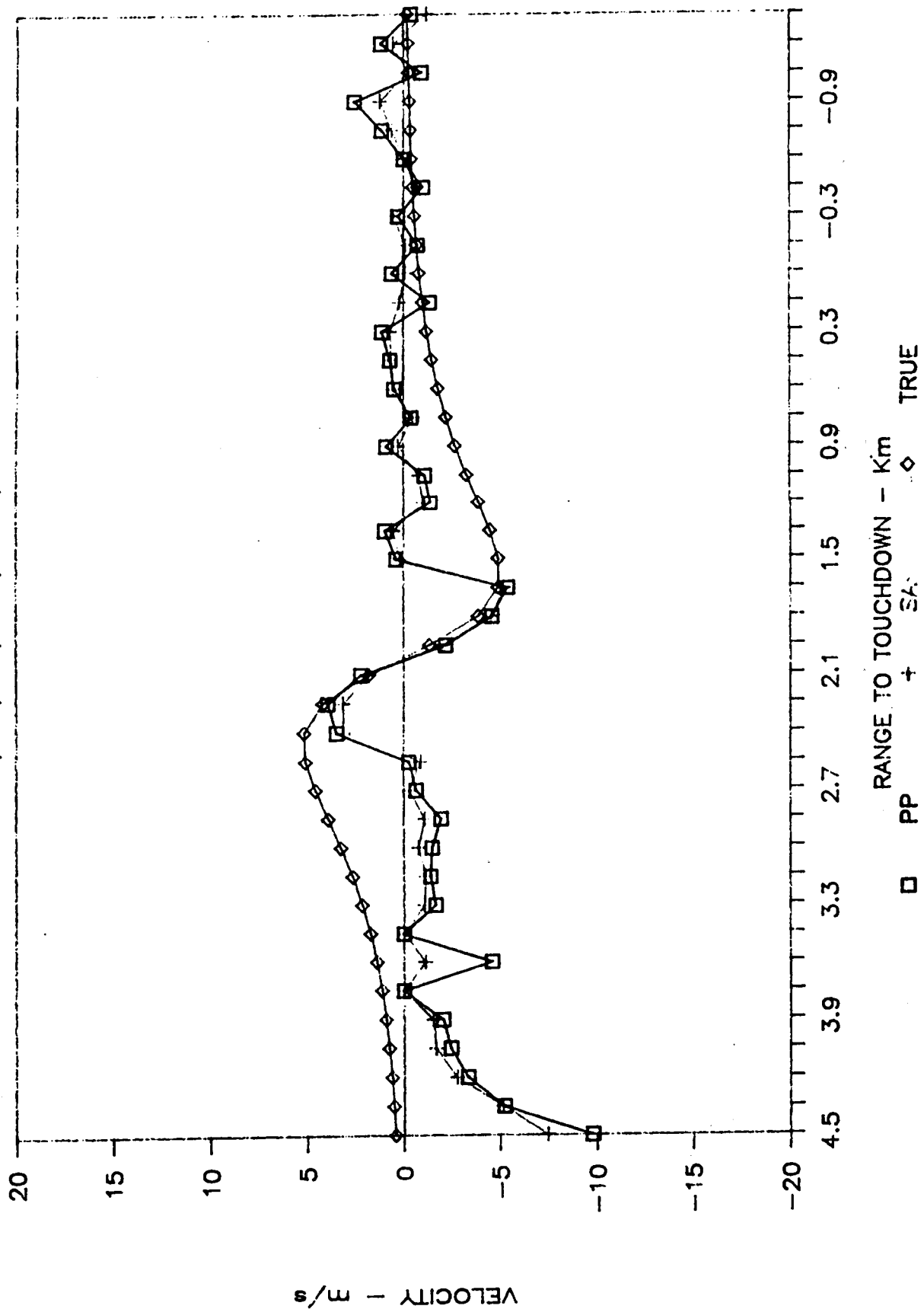
3SIM5,B23,YIPAAZ=0,TILT=1,F=15





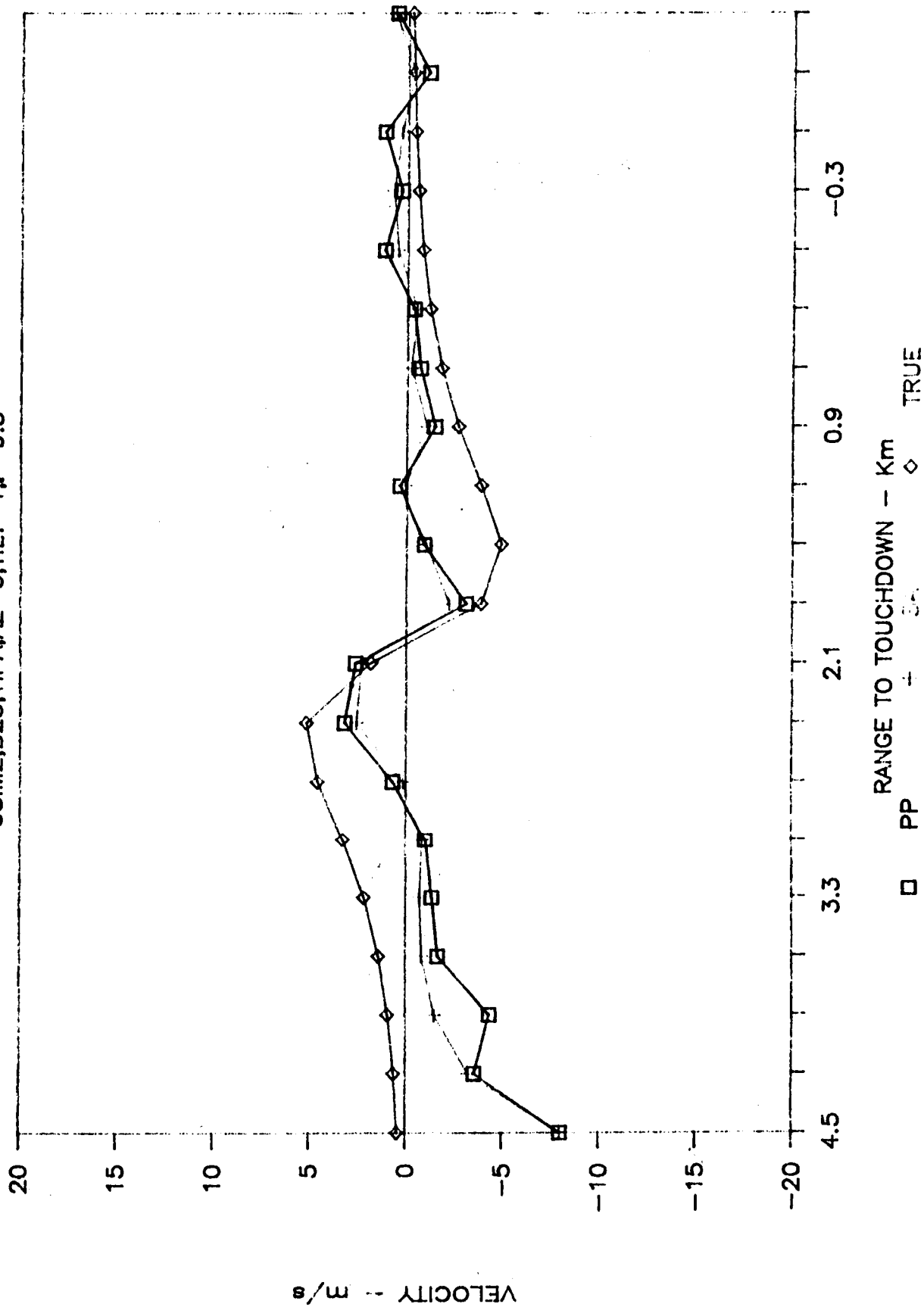
# MEASURED WIND VELOCITY -- m/s

3SIM2,B23,YIPA,AZ=0,TILT=1,F=9.3



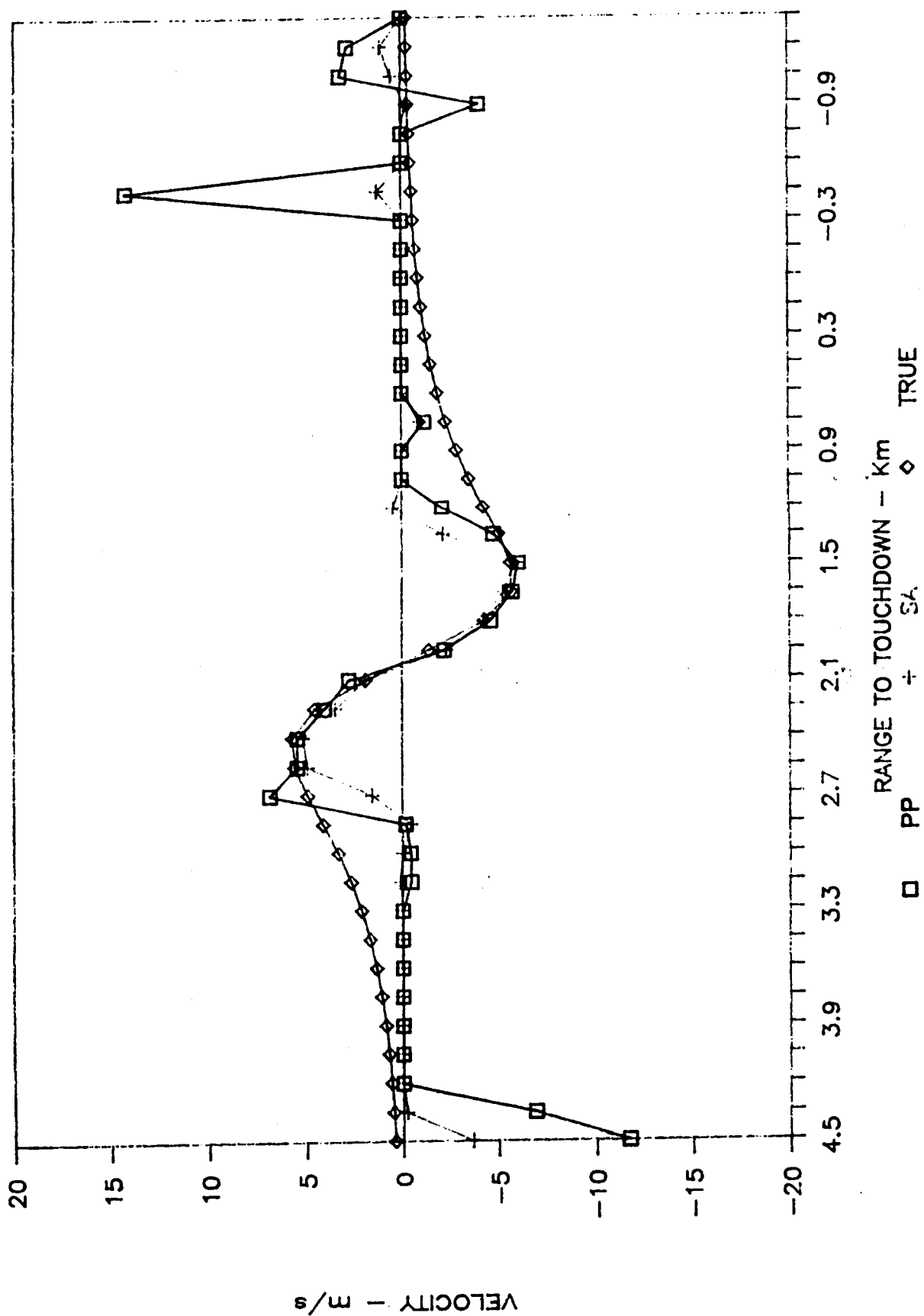
# MEASURED WIND VELOCITY - m/s

5SIM2,B23,YiPA,AZ=0,TILT=1,F=9.3



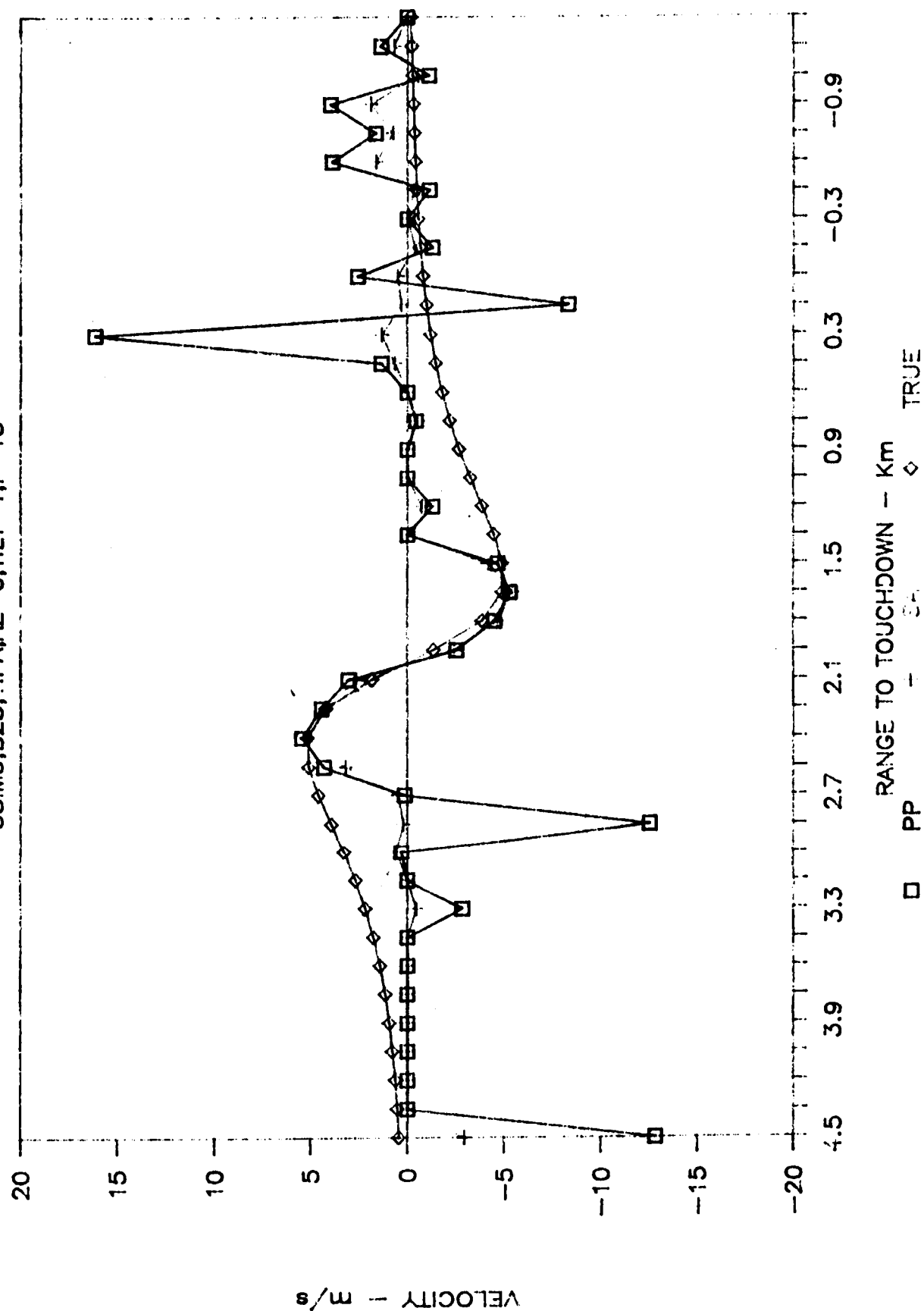
# MEASURED WIND VELOCITY - m/s

4SIM2,B23,YIPA,AZ=0,TILT=2,F=9.3



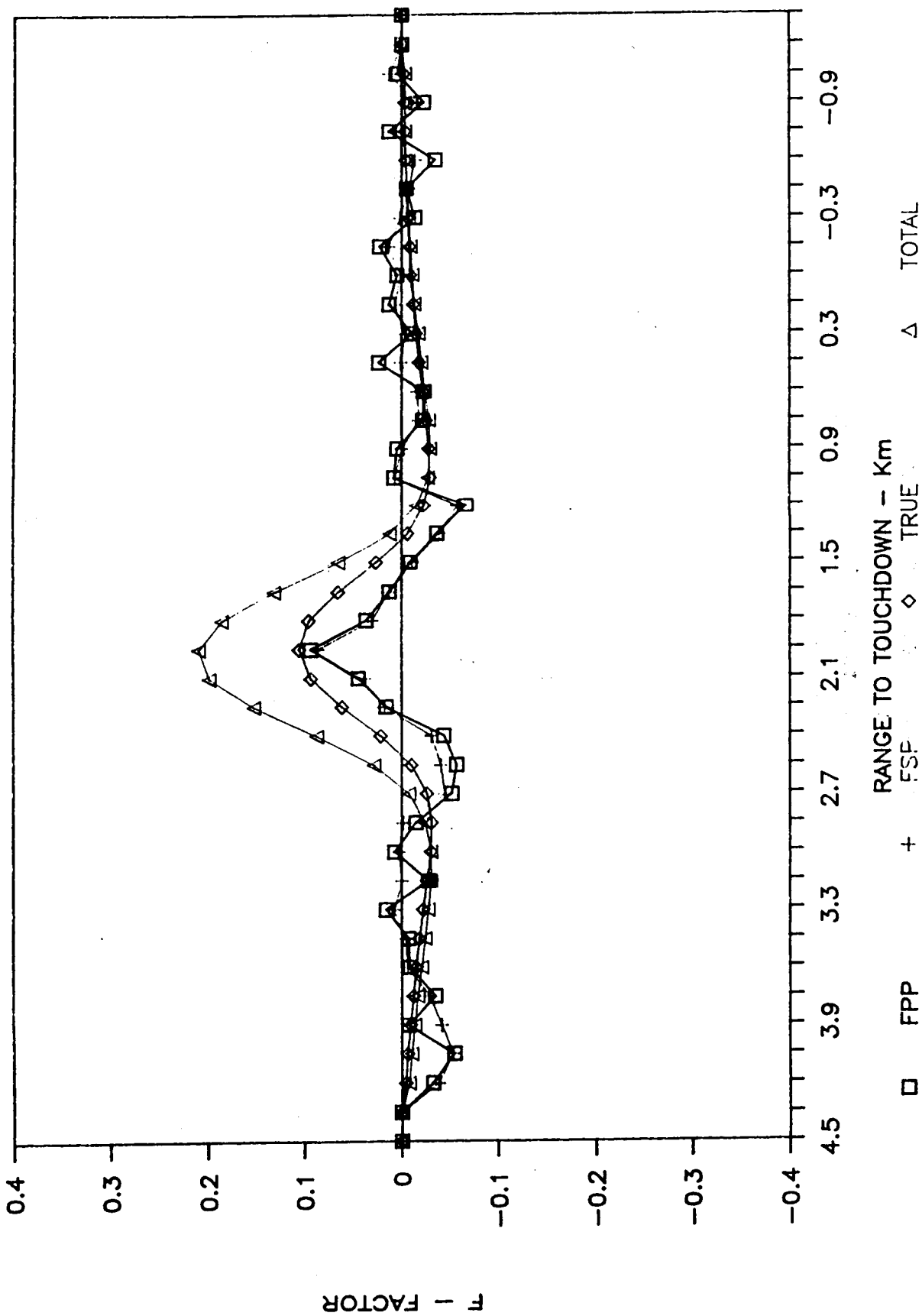
# MEASURED WIND VELOCITY - m/s

3SIM5,B23,YIPA,AZ=0,TILT=1,F=15



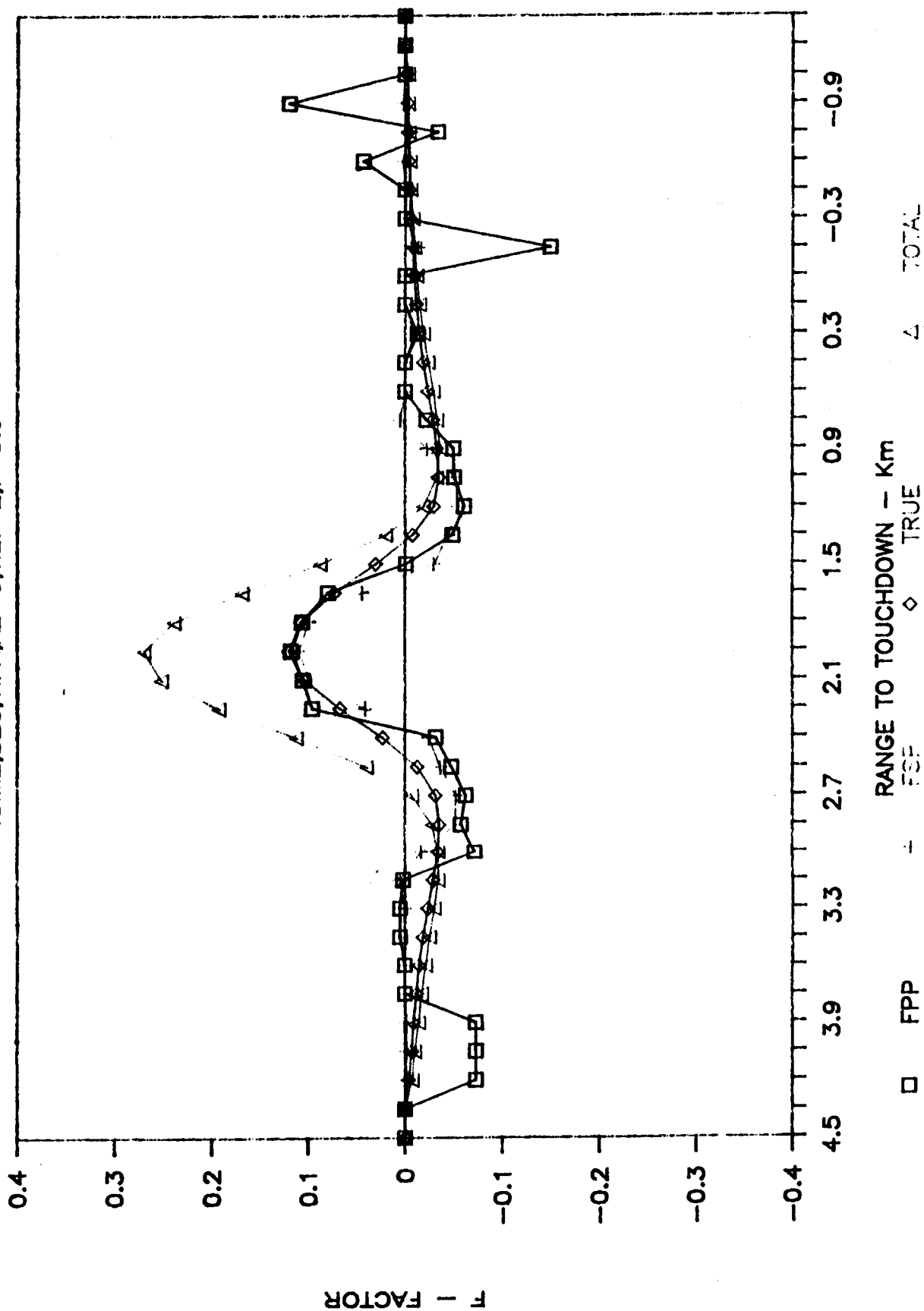
# HAZARD FACTOR VS. RANGE

3SIM2,B23,YIPA,AZ=0,TILT=1,F=9.3



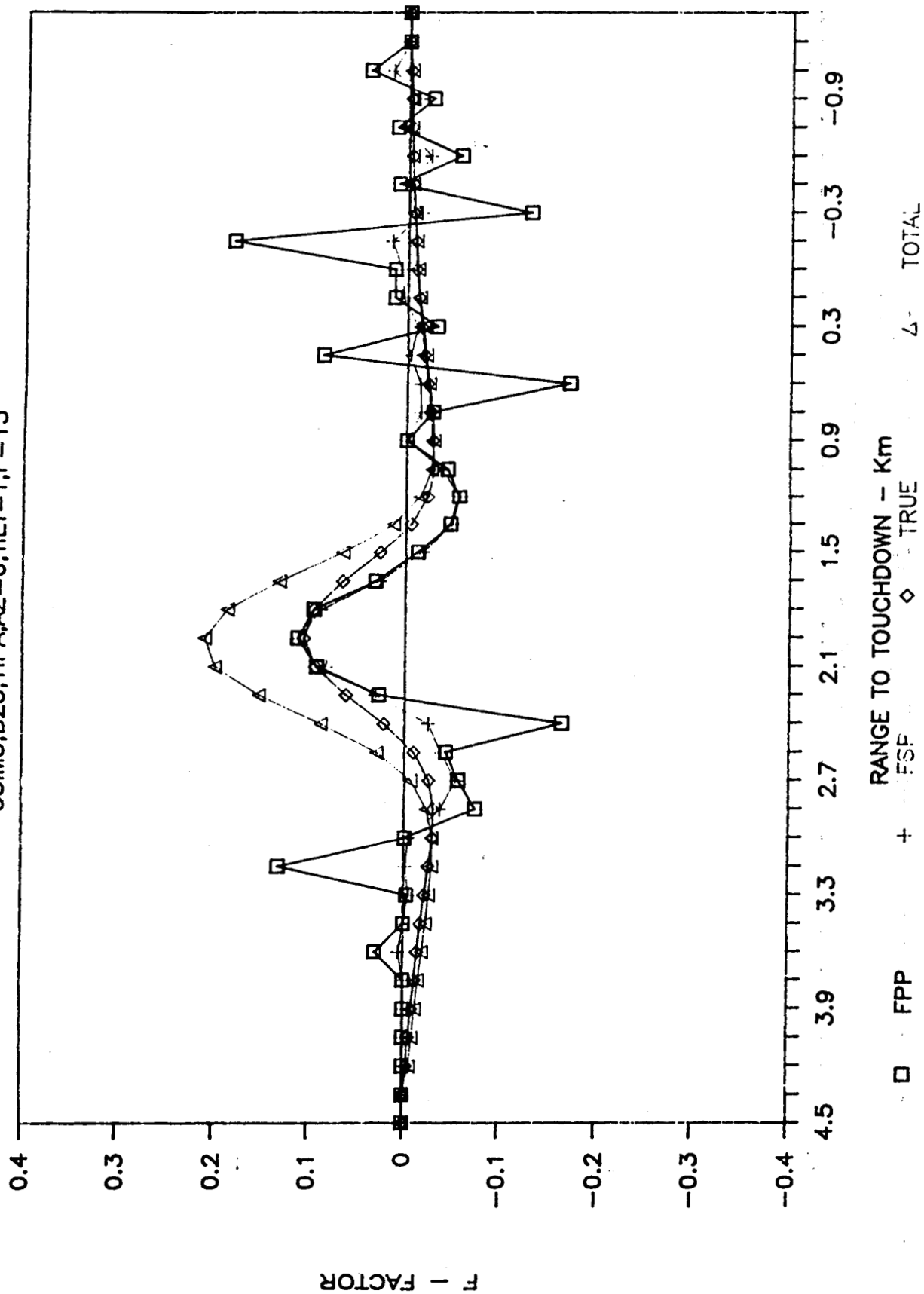
# HAZARD FACTOR VS. RANGE

4SIM2,B23,Y1PA,AZ=0,TILT=2,F=9.3

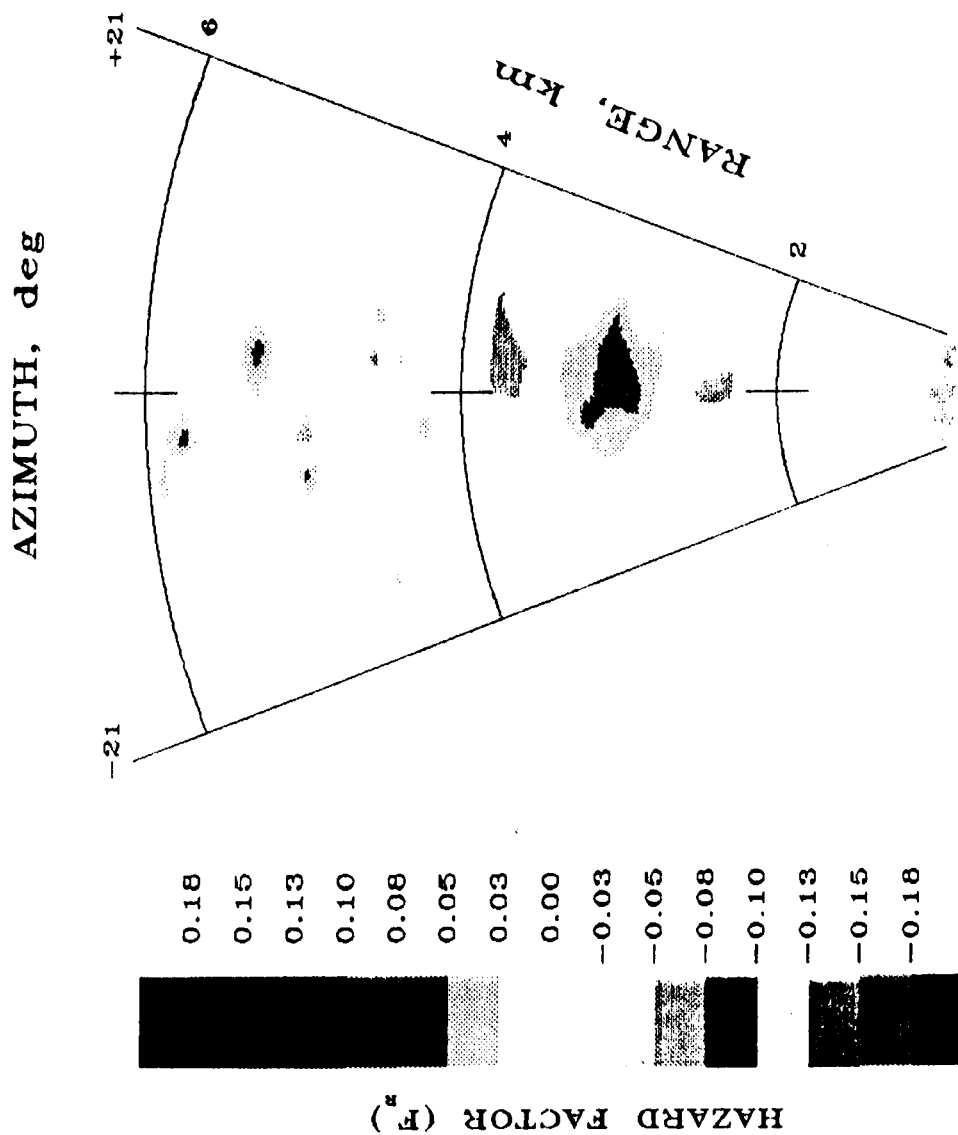


# HAZARD FACTOR VS. RANGE

3SIM5,B23,YIPA,AZ=0,TILT=1,F=15



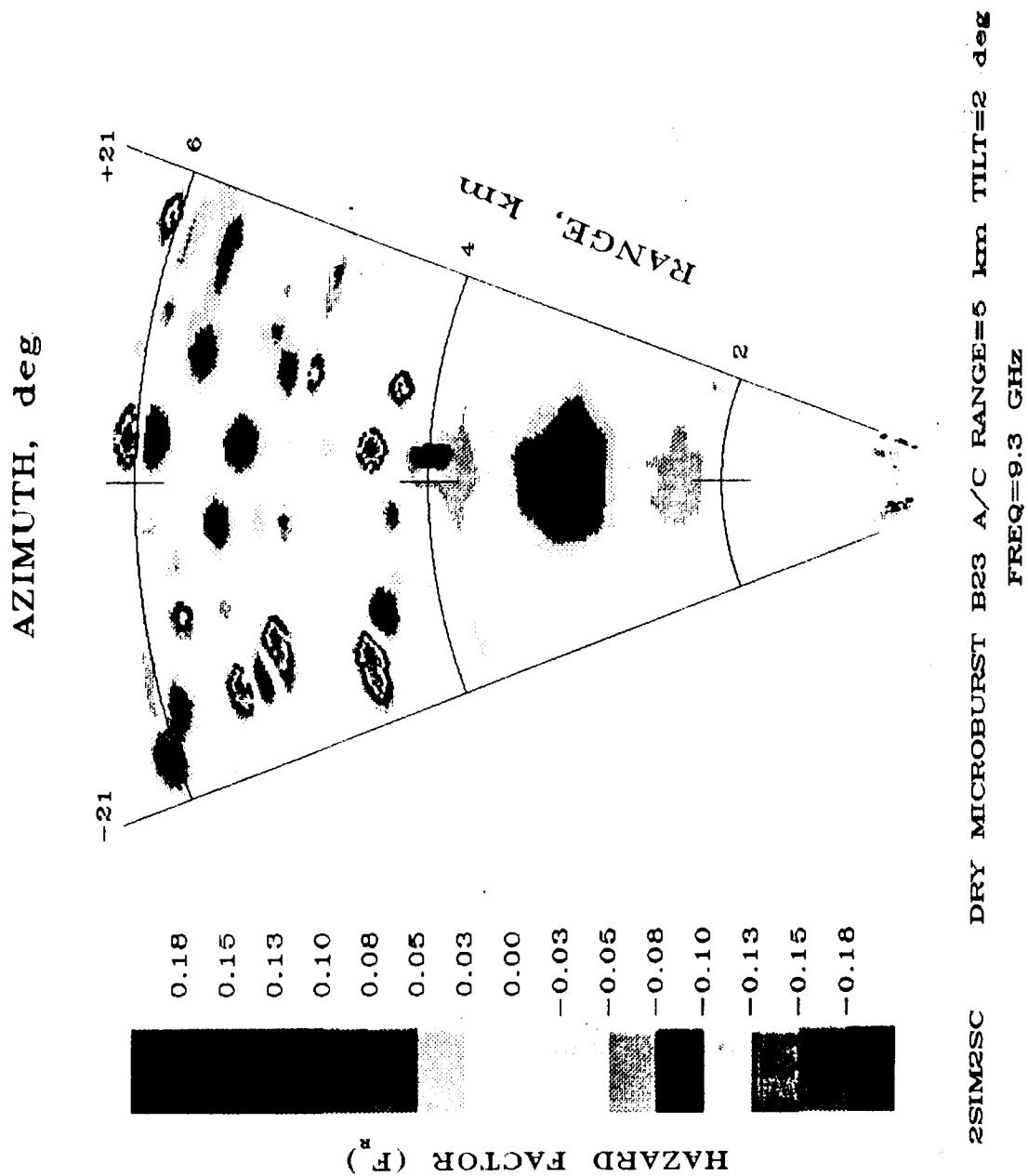
# WINDSHEAR RADAR HAZARD INDEX



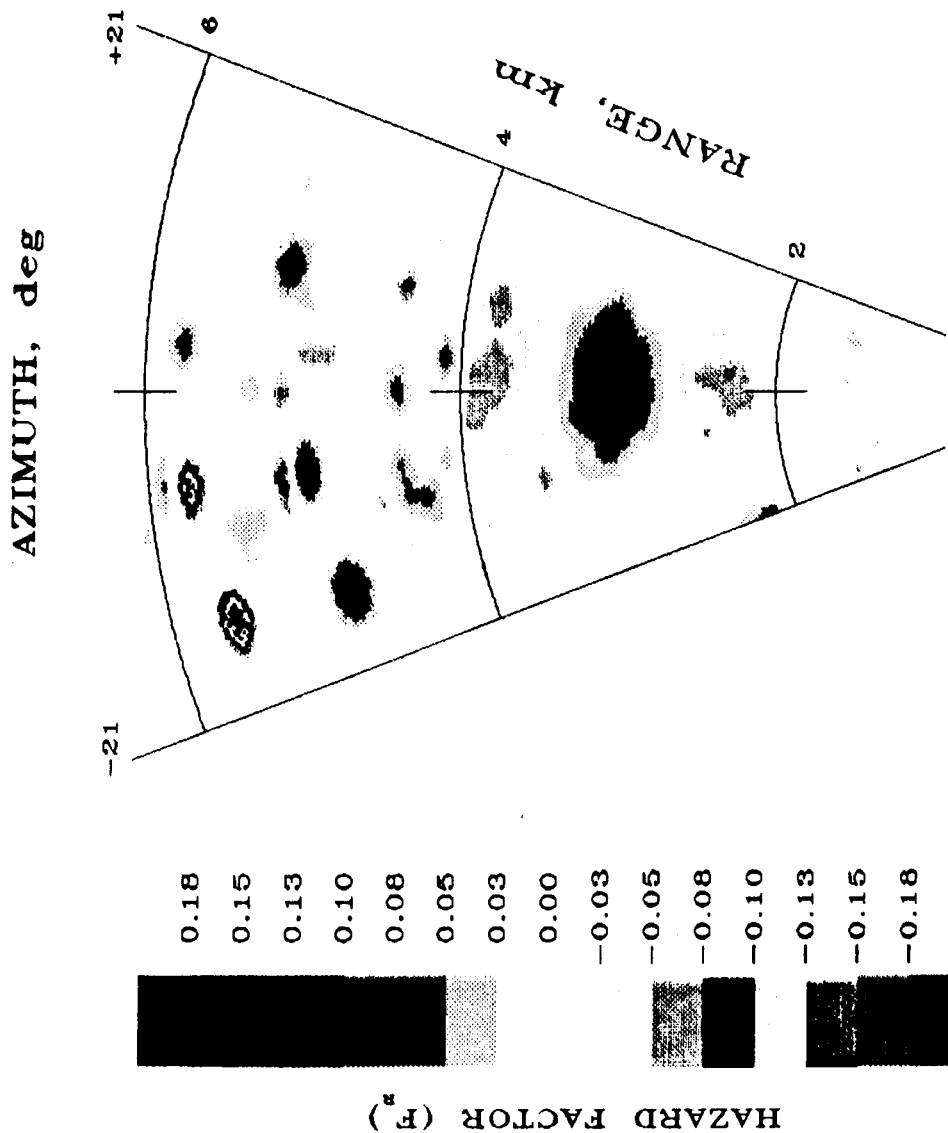
1SIM2SC DRY MICROBURST B23 A/C RANGE=5 km TILT=1 deg  
FREQ=9.3 GHz



# WINDSHEAR RADAR HAZARD INDEX



# WINDSHEAR RADAR HAZARD INDEX



2SIM4SC DRY MICROBURST B23 A/C RANGE=5 km TILT=1 deg  
FREQ=15 GHz

# CONCLUSIONS

## Initial Simulation Studies Show That:

- Airborne Doppler radar sensor has potential to detect windshear.
- Clutter effects can be minimized using antenna tilt control, range limiting, and clutter filtering.
- "Wet" microburst can be accurately detected ahead of A/C.
- Although the presence of "Dry" microbursts was detected, further study is required.

## **FUTURE WORK:**

- Conduct full radar parameter tradeoff evaluation.
- Investigate effects from moving ground clutter.
- Expand study to more varieties of microburst type and locations.
- Evaluate probability of detection, and missed, nuisance and false alarm rates.
- Investigate various windshear detection and clutter filter concepts.
- Evaluate analytical studies & simulations through flight experiments.

## **Session I. Airborne-Sensors**

**Clutter Filter Design Considerations for Airborne Doppler Radar Detection of Wind Shear**  
E. G. Baxa, Jr., Clemson University

**Second Combined Manufacturer's and Technology  
Airborne Wind Shear Review Meeting**

**October 18-20, 1988**

**CLUTTER FILTER DESIGN CONSIDERATIONS  
FOR  
AIRBORNE DOPPLER RADAR DETECTION OF WINDSHEAR**

by

**E. G. Baxa, Jr.  
Clemson University**

527468  
N91-11690

CLUTTER FILTER DESIGN CONSIDERATIONS  
FOR  
AIRBORNE DOPPLER RADAR DETECTION OF WINDSHEAR

p 30

Ernest G. Baxa, Jr.  
Clemson University  
Clemson, SC 29634-0915

ABSTRACT

The problem of clutter rejection when processing down-looking Doppler radar returns from a low altitude airborne platform is a paramount problem. With radar as a remote sensor for detecting and predicting windshear in the vicinity of an urban airport, dynamic range requirements can exceed 50 dB because of high clutter to signal ratios. This presentation describes signal processing considerations in the presence of distributed and/or discrete clutter interference. Previous analyses have considered conventional range cell processing of radar returns from a rigidly mounted radar platform using either the Fourier or the pulse-pair method to estimate average windspeed and windspeed variation within a cell. Clutter rejection has been based largely upon analyzing a particular environment in the vicinity of the radar and employing a variety of techniques to reduce interference effects including notch filtering, Fourier domain line editing, and use of clutter maps. For the airborne environment the clutter characteristics may be somewhat different. Conventional clutter rejection methods may have to be changed and new methods will probably be required to provide useful signal to noise ratios. Various considerations are described. A major thrust has been to evaluate the effect of clutter rejection filtering upon the ability to derive useful information from the post filter radar data. This analysis software is briefly described. Finally, some ideas for future analysis are considered including the use of adaptive filtering for clutter rejection and the estimation of windspeed spatial gradient directly from radar returns as a means of reducing the effects of clutter on the determination of a windshear hazard.

CLUTTER FILTER DESIGN CONSIDERATIONS  
FOR  
AIRBORNE DOPPLER RADAR DETECTION OF WINDSHEAR

Ernest G. Baxa, Jr.  
Clemson University  
Clemson, SC 29634-0915

OUTLINE

- I. The Clutter Problem
  - A. Radar antenna sidelobes causes high clutter levels
  - B. Moving radar platform influences spectrum widths
  - C. Discrete clutter sources in the urban environment
- II. Review of Past Clutter Rejection Research
  - A. Notch filtering at zero Doppler
  - B. Fourier line editing
  - C. Geographical clutter maps
- III. Clutter Rejection for Airbourne Radar
  - A. Notch filter requirements
    - 1. zero gain at zero Doppler
    - 2. transient response short
    - 3. notch width considerations
    - 4. dynamic range requirements
    - 5. non-stationarity
  - B. Fourier line editing
    - 1. mid-band discrete clutter
    - 2. computational load
  - C. Geographical clutter maps
    - 1. poor repeatability
  - D. Antenna Steering
  - E. Adaptive Filters
  - F. Non-conventional Signal Processing
    - 1. estimating windspeed gradient directly
    - 2. hazard detection and estimation
- IV. Effects of Clutter Rejection On Signal Parameter Estimation
  - A. Computer software development
    - 1. filtering in time or frequency domain
    - 2. repeated trials
    - 3. simulated or real data
  - B. Pulse-pair estimation of spectral parameters
    - 1. ideal notch filter
    - 2. simple IIR filters
    - 3. phase response constraints
    - 4. the pulse canceller
- V. Summary and Conclusions



**Clutter Filter Design Considerations For  
Airborne Doppler Radar Detection of Windshear  
October 19, 1988**

**Clutter Filter Design Considerations  
for  
Airborne Doppler Radar Detection of Windshear**

by

**E.G. Baxa, Jr.  
Clemson University**

**2nd CMTAW meeting**

**Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University**

**Oct. 19, 1988**

**OUTLINE**

- **The Clutter Problem**
- **Review of Past Clutter Rejection Research**
- **Clutter Rejection for Airborne Radar**
- **Effects of Clutter Rejection On Signal Parameter Estimation**
- **Summary and Conclusions**

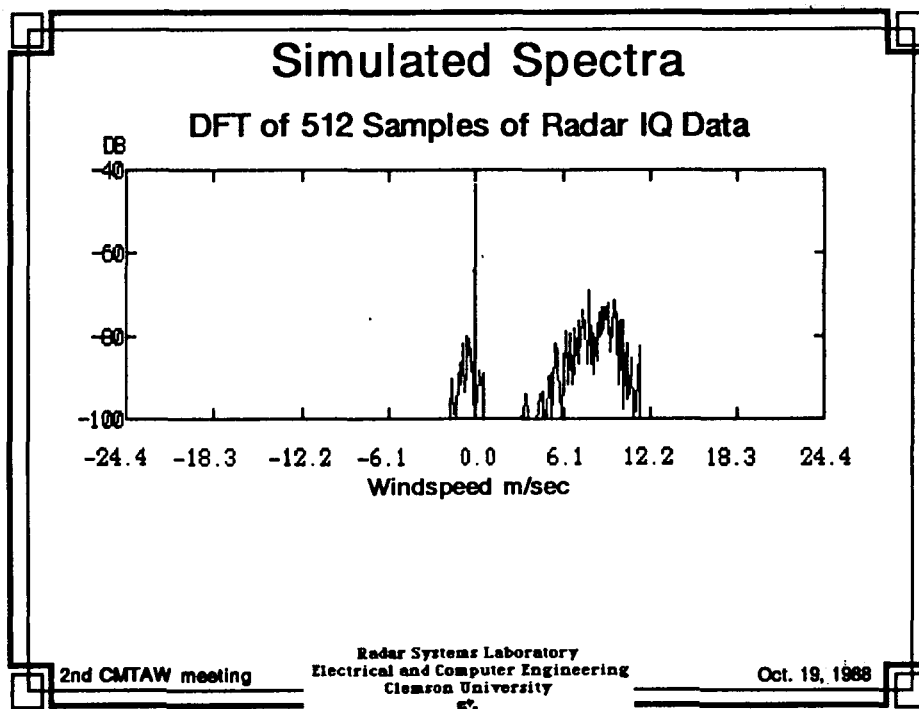
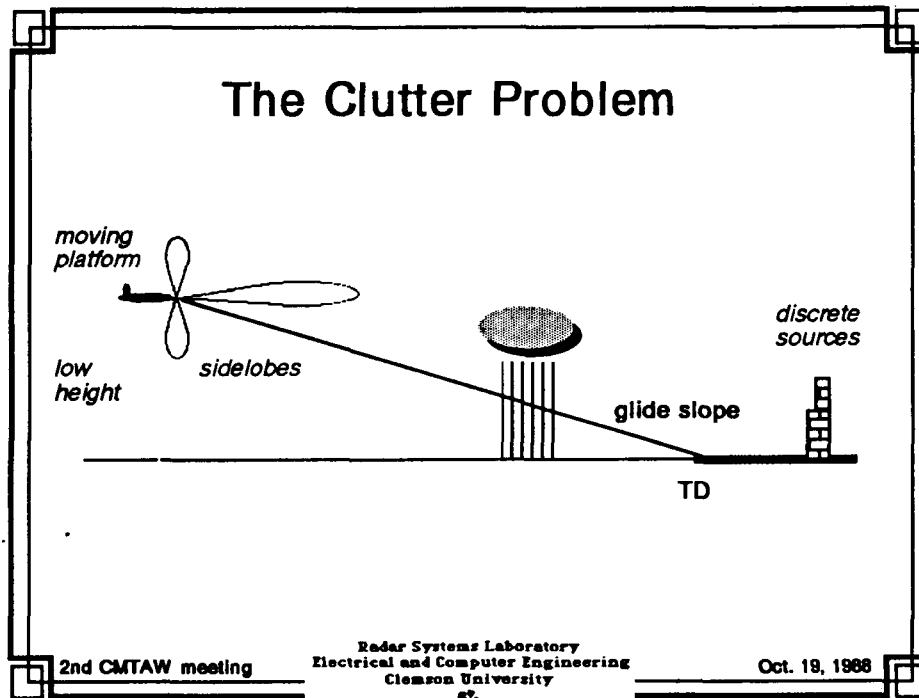
**2nd CMTAW meeting**

**Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University**

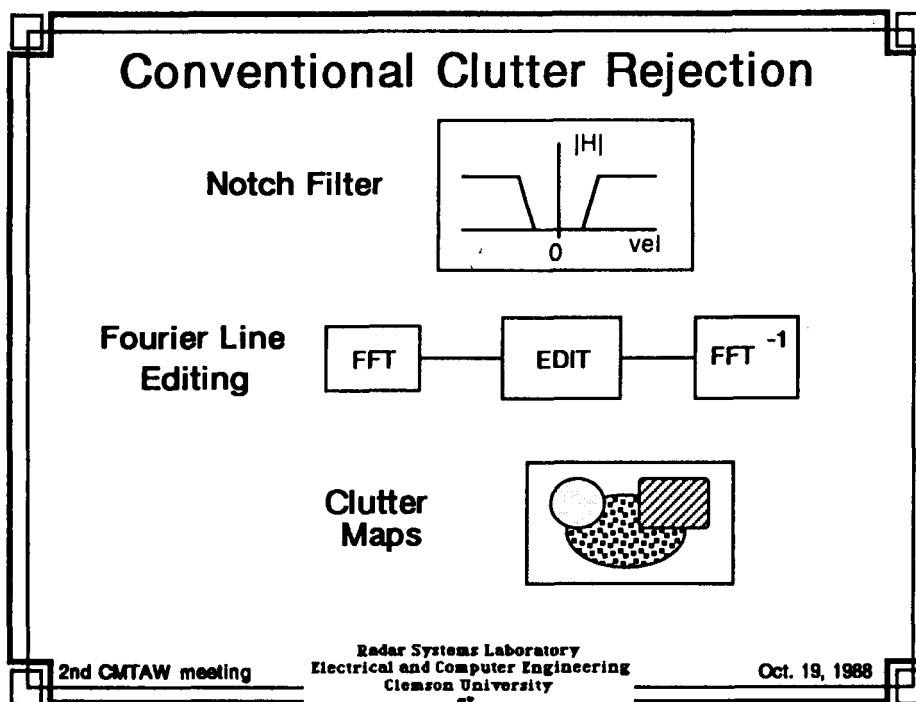
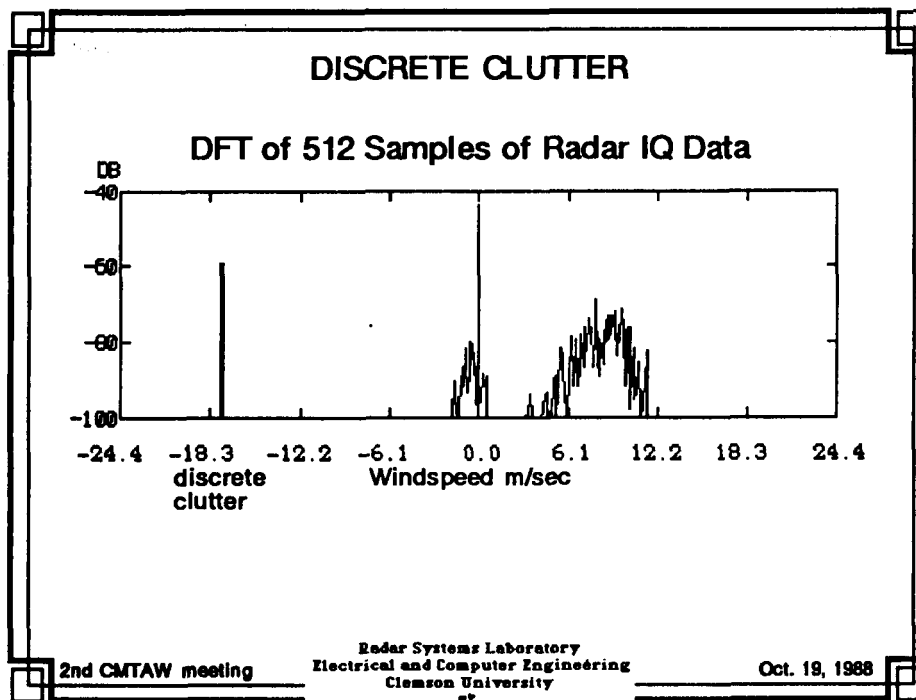
**Oct. 19, 1988**

# Clutter Filter Design Considerations For Airborne Doppler Radar Detection of Windshear

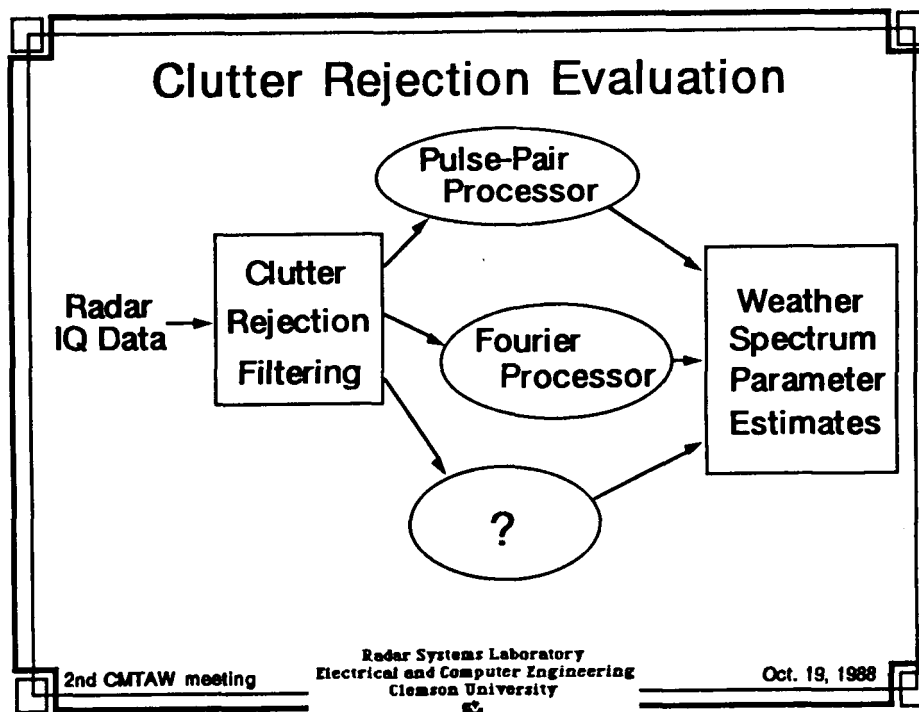
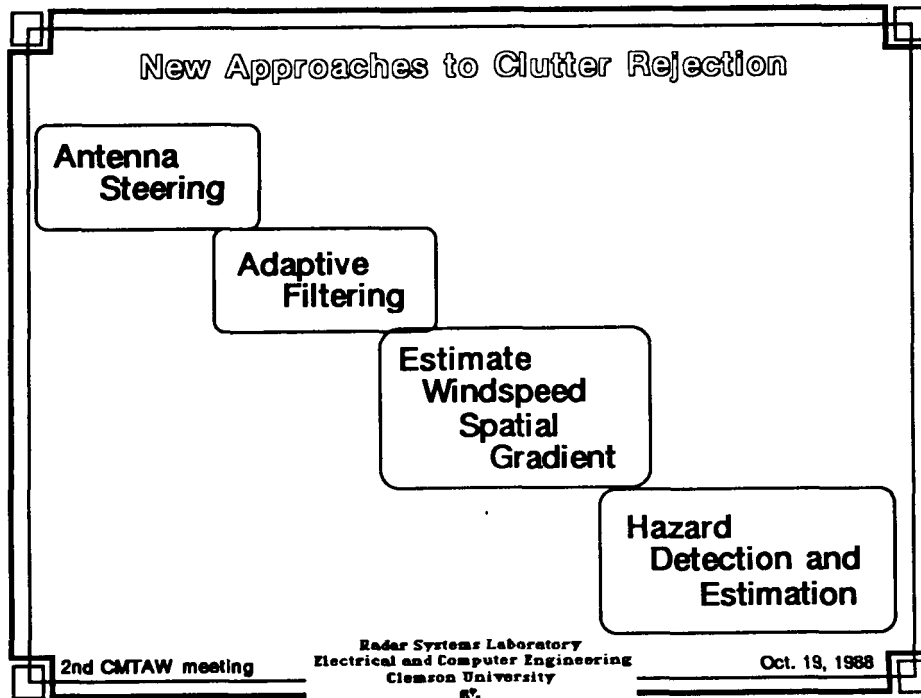
October 19, 1988



# Clutter Filter Design Considerations For Airborne Doppler Radar Detection of Windshear October 19, 1988

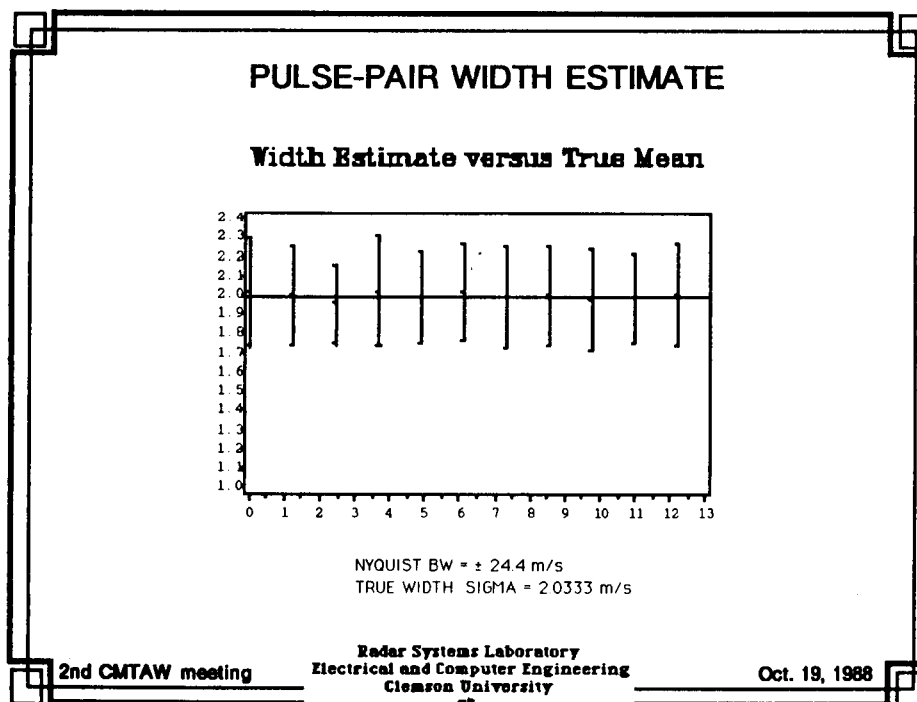
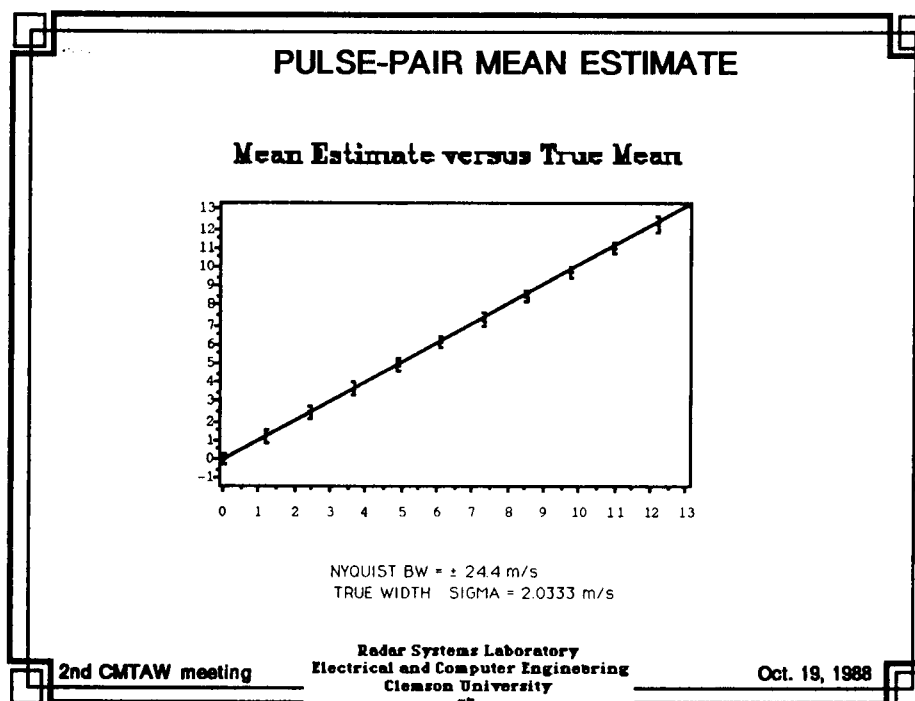


# Clutter Filter Design Considerations For Airborne Doppler Radar Detection of Windshear October 19, 1988



# Clutter Filter Design Considerations For Airborne Doppler Radar Detection of Windshear

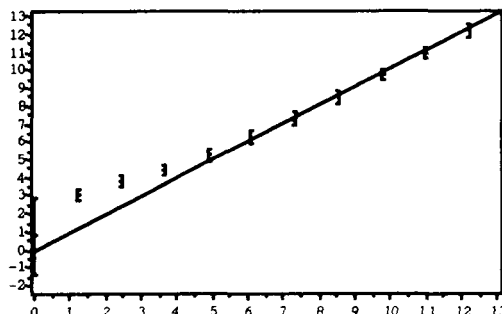
October 19, 1988



# Clutter Filter Design Considerations For Airborne Doppler Radar Detection of Windshear October 19, 1988

## PULSE-PAIR MEAN WITH IDEAL NOTCH FILTER

Mean Estimate versus True Mean



NYQUIST BW =  $\pm 24.4$  m/s  
TRUE WIDTH SIGMA = 2.0333 m/s  
IDEAL FILTER NOTCH BW = 2.44 m/s

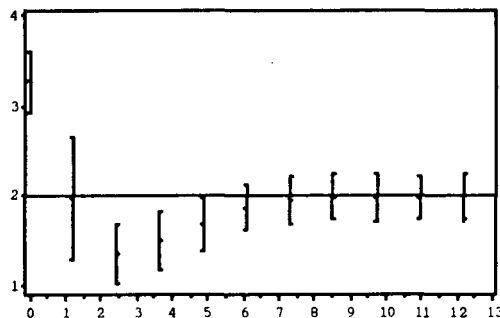
2nd CMTAW meeting

Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

Oct. 19, 1988

## PULSE-PAIR WIDTH WITH IDEAL NOTCH FILTER

Width Estimate versus True Mean



NYQUIST BW =  $\pm 24.4$  m/s  
TRUE WIDTH SIGMA = 2.0333 m/s  
IDEAL FILTER NOTCH BW = 2.44 m/s

2nd CMTAW meeting

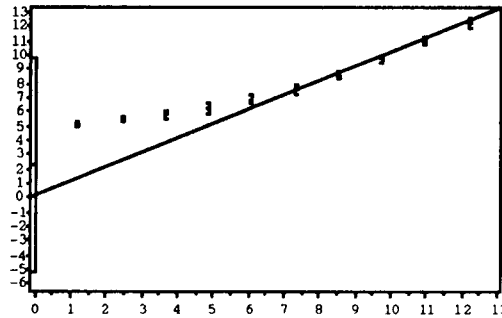
Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

Oct. 19, 1988

# Clutter Filter Design Considerations For Airborne Doppler Radar Detection of Windshear October 19, 1988

## PULSE PAIR MEAN WITH 4 m/s IDEAL NOTCH

Mean Estimate versus True Mean



NYQUIST BW =  $\pm 24.4$  m/s  
TRUE WIDTH SIGMA = 2.0333 m/s  
IDEAL FILTER NOTCH BW = 488 m/s

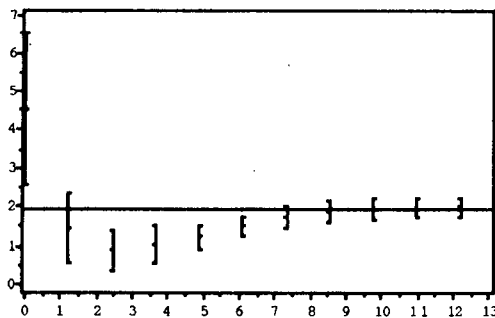
2nd CMTAW meeting

Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

Oct. 19, 1988

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2nd CMTAW meeting

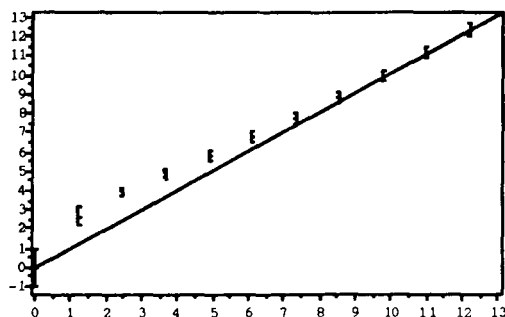
Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

Oct. 19, 1988

# Clutter Filter Design Considerations For Airborne Doppler Radar Detection of Windshear October 19, 1988

## PULSE-PAIR MEAN WITH BUTTERWORTH NOTCH FILTER

Mean Estimate versus True Mean



NYQUIST BW =  $\pm 244$  m/s  
TRUE WIDTH SIGMA = 2.0333 m/s  
 $y(n) = 0.5 * y(n-1) + x(n) - x(n-1)$

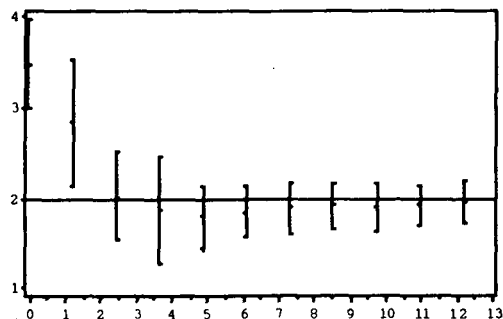
2nd CMTAW meeting

Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

Oct. 19, 1988

## PULSE-PAIR WIDTH WITH BUTTERWORTH NOTCH FILTER

Width Estimate versus True Mean



NYQUIST BW = 244 m/s  
TRUE WIDTH SIGMA = 2.0333 m/s  
 $y(n) = 0.5 * y(n-1) + x(n) - x(n-1)$

2nd CMTAW meeting

Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

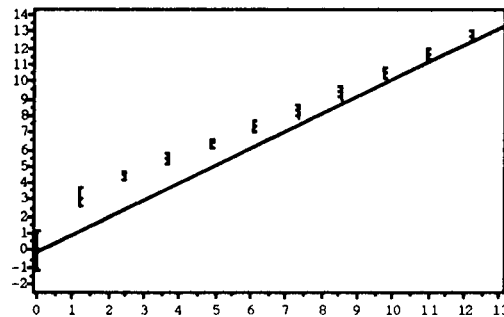
Oct. 19, 1988



# Clutter Filter Design Considerations For Airborne Doppler Radar Detection of Windshear October 19, 1988

## PULSE-PAIR MEAN WITH PULSE CANCELLER

Mean Estimate versus True Mean



NYQUIST BW =  $\pm 24.4$  m/s  
TRUE WIDTH SIGMA = 20333 m/s  
 $y(n) = x(n) - x(n - 1)$

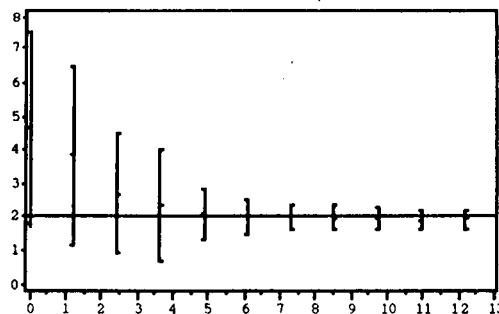
2nd CMTAW meeting

Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

Oct. 19, 1988

## PULSE-PAIR WIDTH WITH PULSE CANCELLER

Width Estimate versus True Mean



NYQUIST BW =  $\pm 24.4$  m/s  
TRUE WIDTH SIGMA = 20333 m/s  
 $y(n) = x(n) - x(n - 1)$

2nd CMTAW meeting

Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

Oct. 19, 1988

**Clutter Filter Design Considerations For  
Airborne Doppler Radar Detection of Windshear  
October 19, 1988**

***SUMMARY***

- **Airborne Environment Has Unique Problems**

large clutter to signal ratios  
dynamic range requirements  
non-stationarities  
lack of repeatability

- **Optimized Signal Processing Schemes are  
Needed and are Feasible**

2nd CMTAW meeting

Radar Systems Laboratory  
Electrical and Computer Engineering  
Clemson University

Oct. 18, 1988

## **Session I. Airborne—Sensors**

**Airborne Radar Scatterometer Design & Flight Test**  
**W. R. Jones and C. D. Lytle, NASA LaRC**

# ***FLIGHT TEST PROGRAM***

***October 19, 1988***

***W.R. Jones***

# ***FLIGHT PROGRAM TASKS***

- Develop an Airborne Research Radar instrument including:
  - Antenna pointing
  - Instrument evaluation
  - Algorithm development
- Conduct aircraft flights to obtain:
  - Airport clutter data
  - Wind Shear data from convective storms
  - Combined Wind Shear & Clutter Data
- Real time demonstration is being considered for evaluating potential sensor concepts. Effort would evaluate signal processing algorithms with results available to industry.

# ***FLIGHT TEST PROGRAM***

## **PHASE I (Clutter Characterization)**

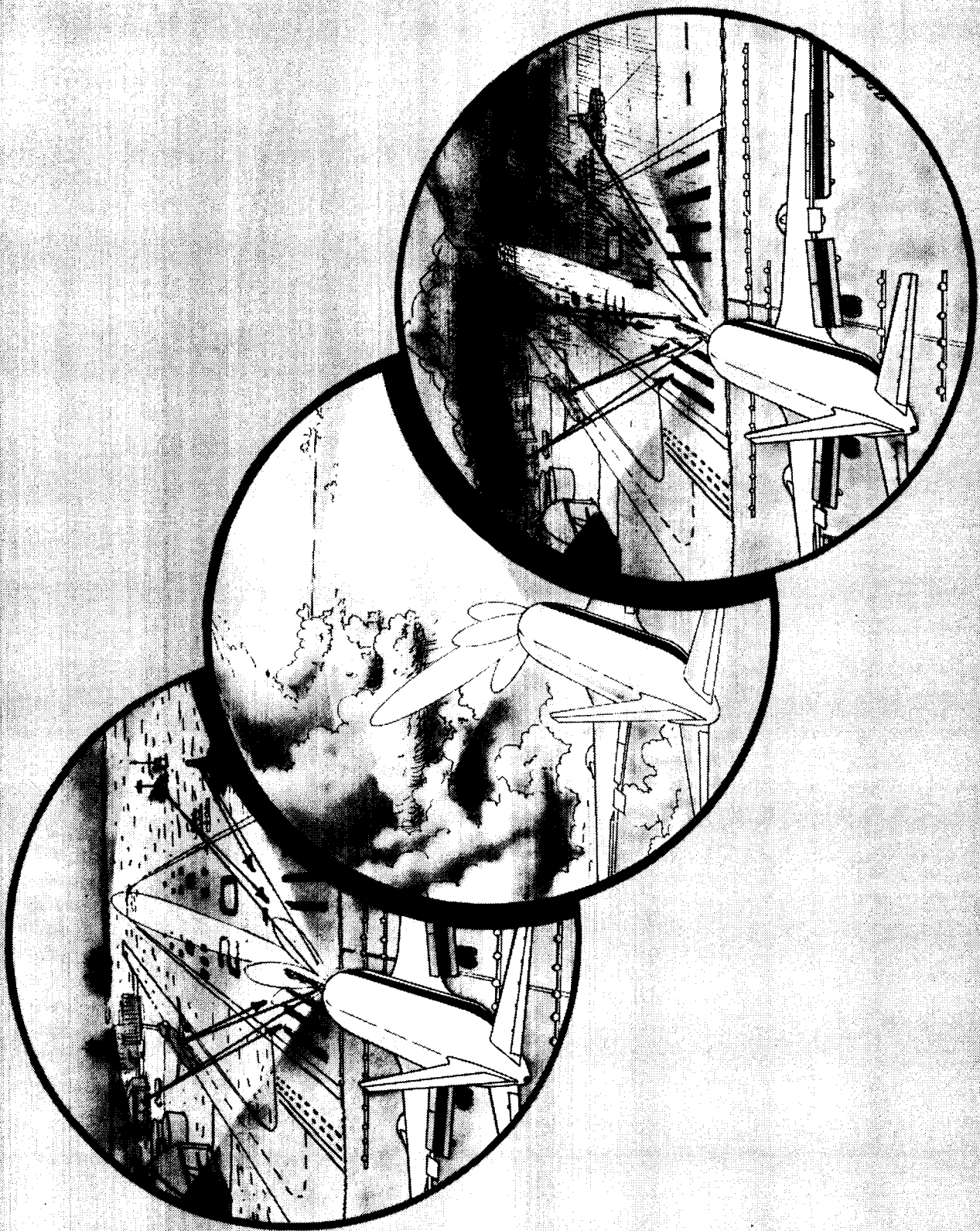
- Radar backscatter from airport ground clutter during landing approaches.

## **PHASE II (Wind Shear Detection)**

- Radar rain backscatter doppler data without ground clutter.

## **PHASE III (Wind Shear Detection With Clutter)**

- Combined radar rain backscatter and clutter measurements.



# PHASE I

Goal: Characterize Clutter for Airports of Interest.

CONDITIONS: For selected airport/s

- collect data in clear weather in landing approach path
- From altitudes of 2000 to 200 feet
- From 5 miles out to airport along 3 deg. glide slope
- Using horizontal / vertical polarized X-band system
- With impacts of moving clutter

STATUS:

Test plan being developed, example of plan inputs

## AIRPORTS

Wallops flight facility  
Detroit (Willow Run)  
Denver (Stapleton)  
Philadelphia (International)  
Minneapolis-St. Paul (International)

## INTEREST

Local, convenient, low traffic  
ERIM SAR Data test site





## ***PHASE II***

Present thoughts:

- Probably at Denver
- Supported by NOAA and other ground based Doppler Radars
- Possible flight at Wallops Island

## ***PHASE III***

No detailed plans yet, but would contain demonstration flights at selected airports.

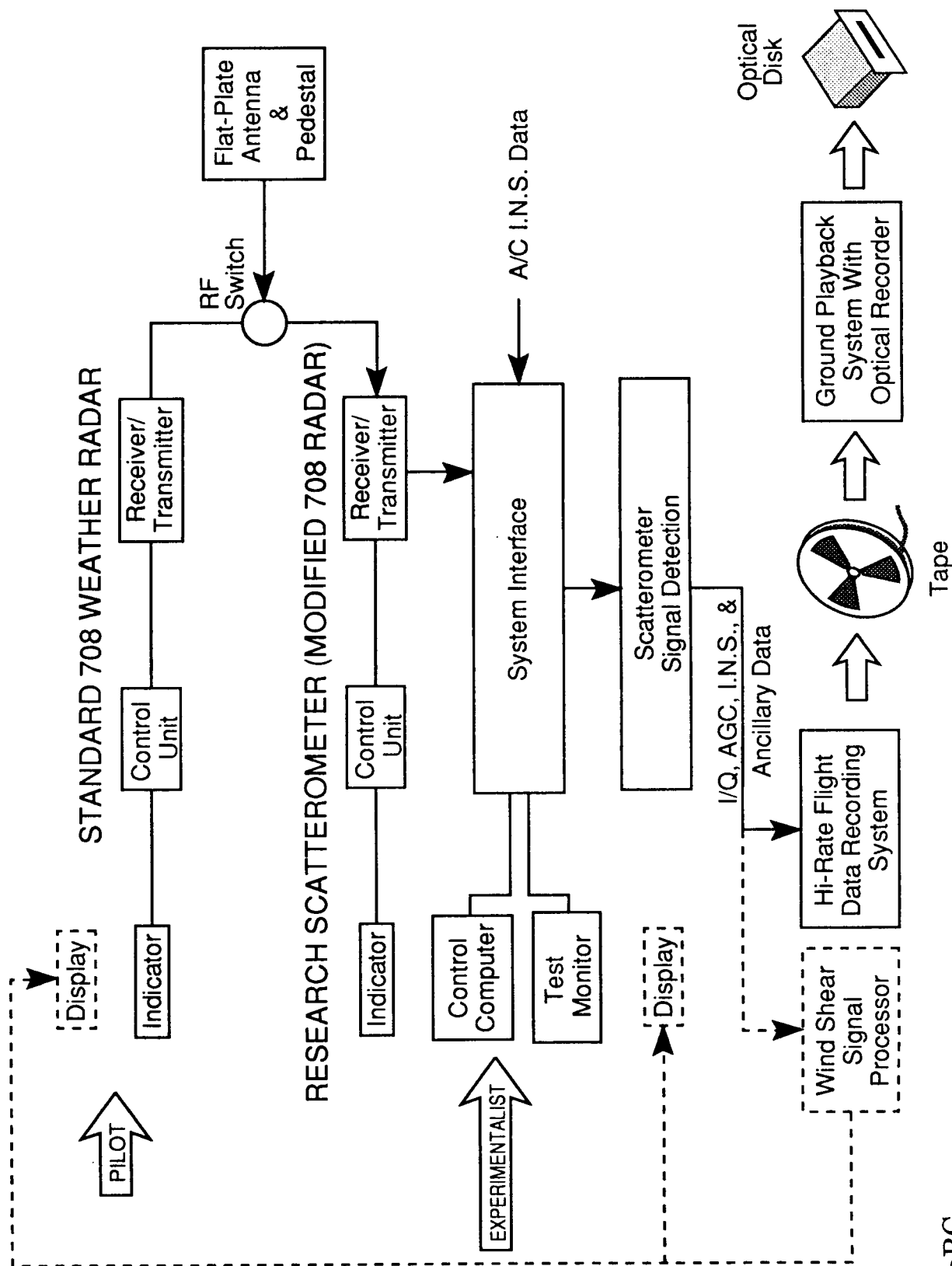
***FLIGHT PROGRAM  
HARDWARE***

***October 19, 1988***

***C.D. LYTLE***

# FLIGHT EXPERIMENT

W-S Radar Program



# EXPERIMENT COMPONENTS LOCATION

R/T unit 2  
(Research)

Flight Deck

Control Unit

Digital Tape Recorder

Boeing 737

Experiment Station

Data Processing

Control Computer

R/T unit 1  
(Standard)

Video

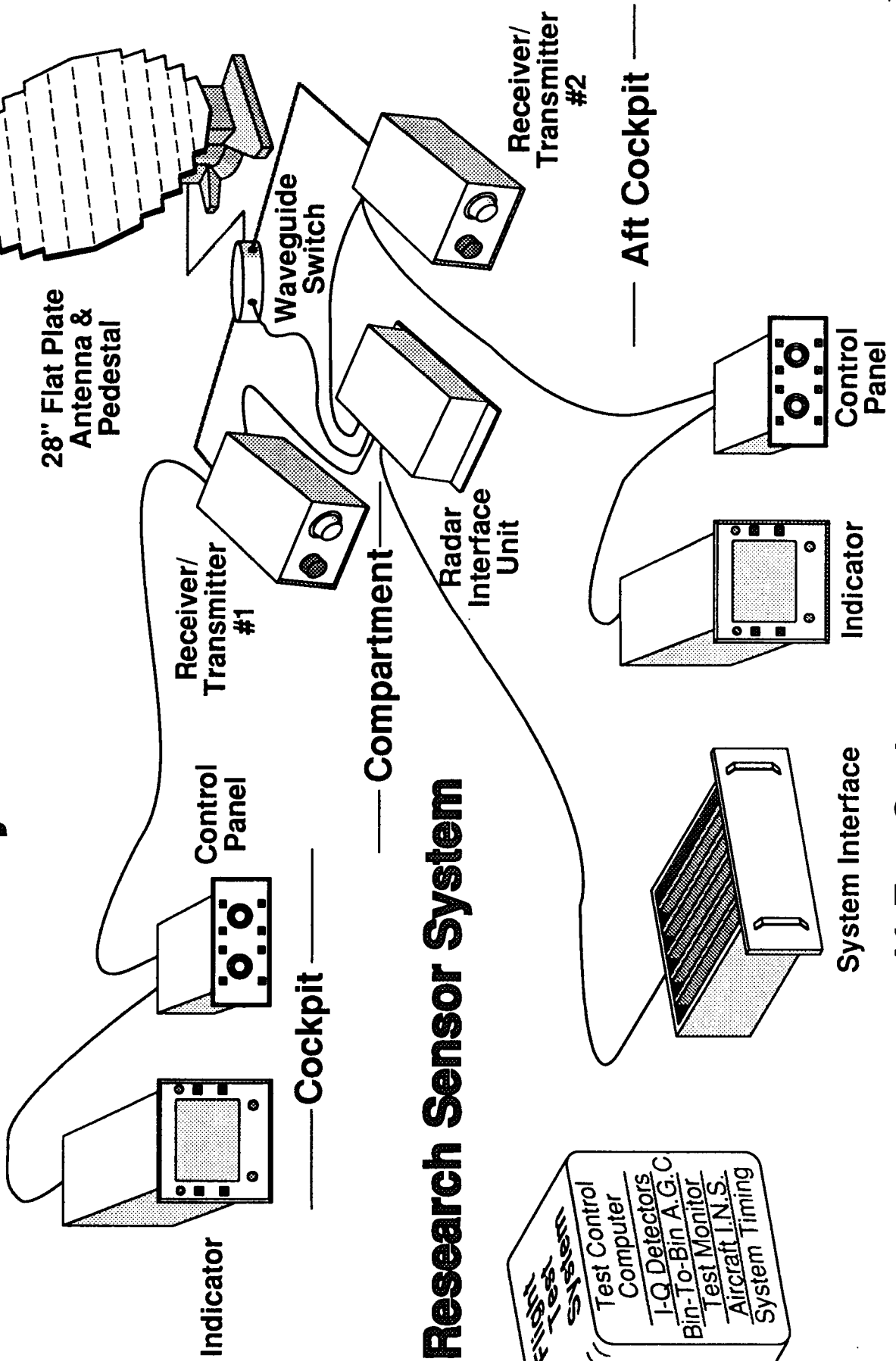
Antenna

Indicator

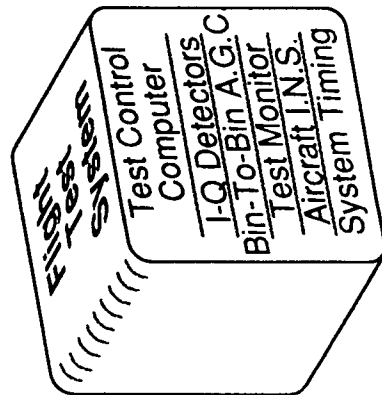
# FLIGHT SENSOR SYSTEM

W-S Radar System

## Aircraft Weather Radar System

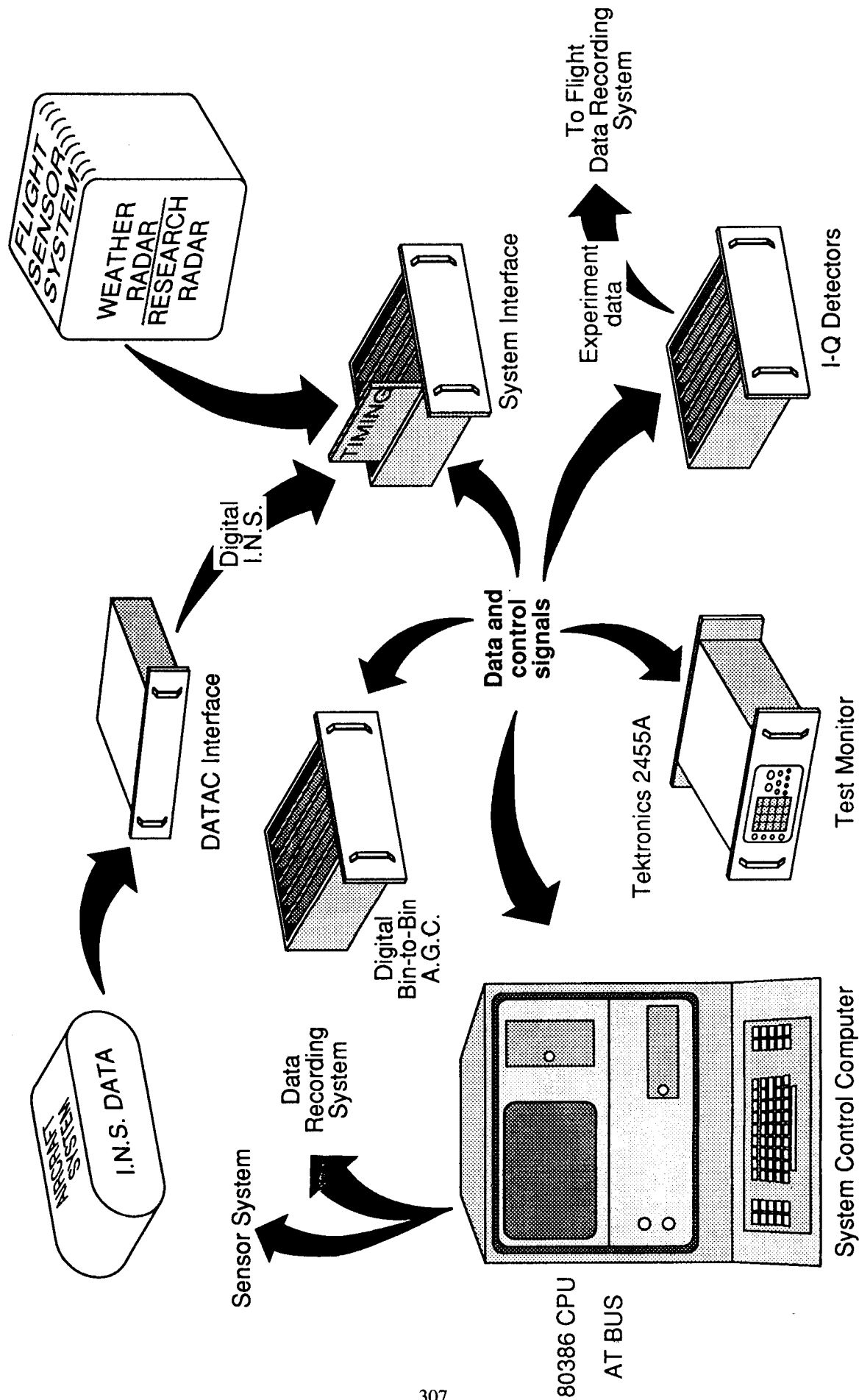


## Research Sensor System



# FLIGHT TEST SYSTEM

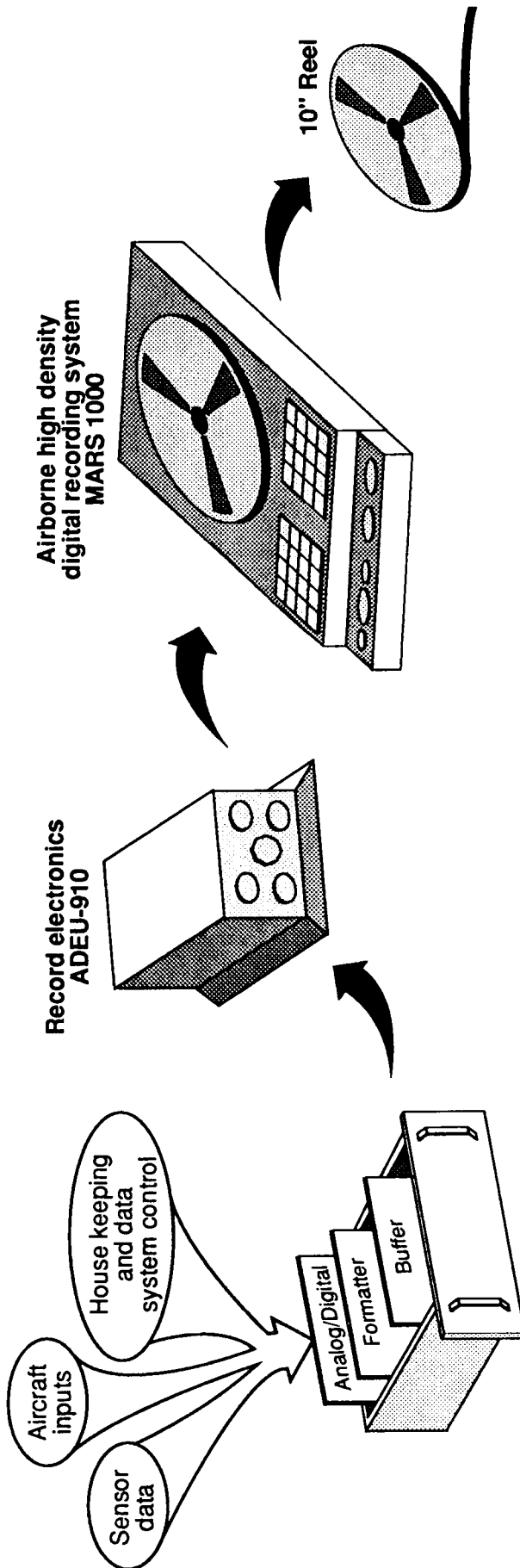
W-S Radar System



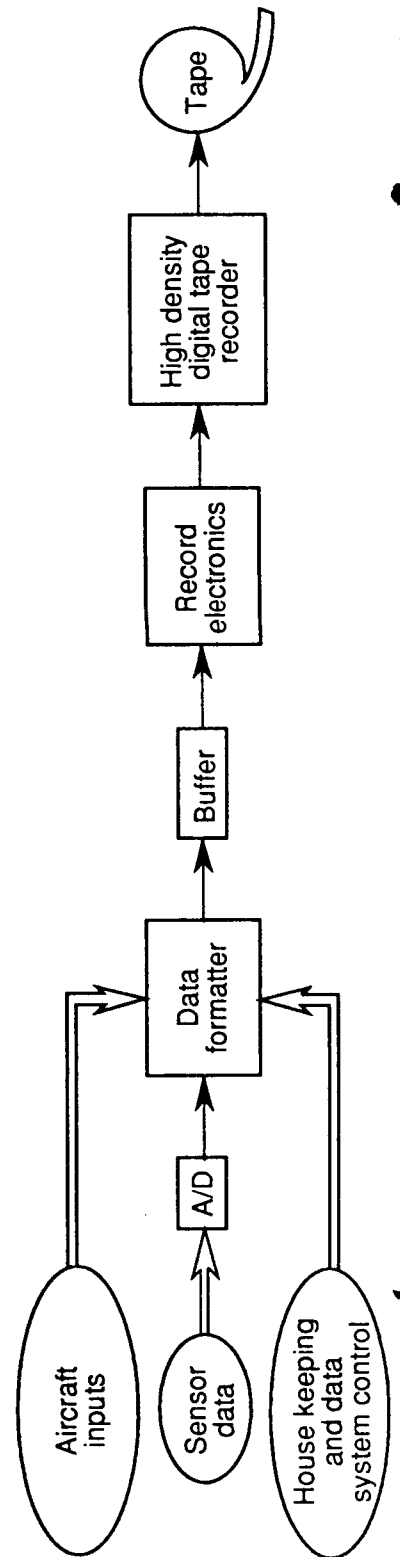
# FLIGHT DATA RECORDING SYSTEM

W-S Radar System

## HARDWARE COMPONENTS



## FUNCTIONAL DIAGRAM



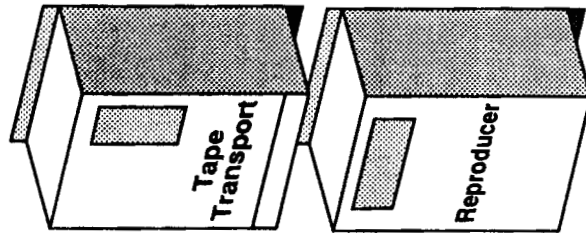
# PLAYBACK SYSTEM

W-S Radar System

10" Reel  
1 x 10<sup>9</sup> Bytes

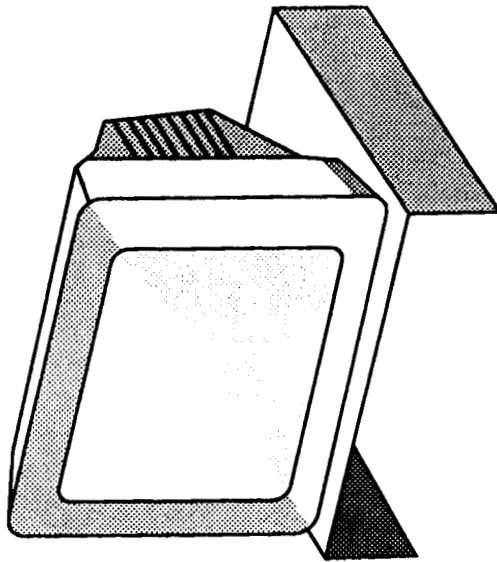


Kodak  
M14-LR  
Datatape  
Airborne/  
Portable  
High Density  
Digital Recorder/  
Reproducer

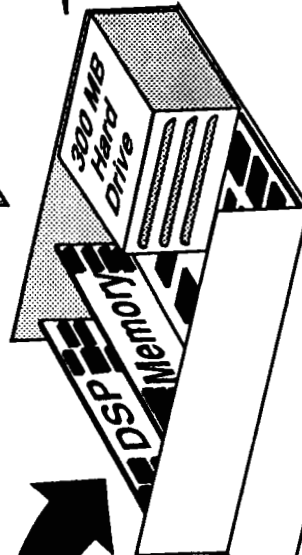


## Hardware Components

COMPAC  
80386



Maxtor  
RXT-800S  
Optical Disk Drive

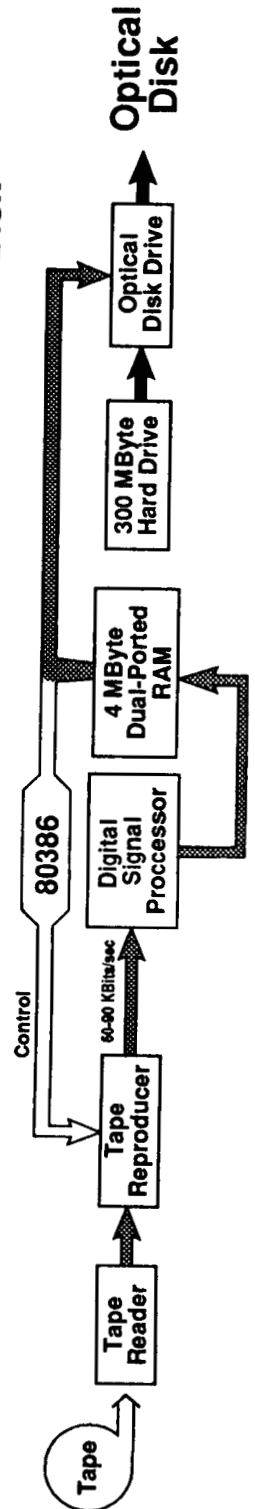


800MB  
5 1/4" Optical  
Disk



To  
Computer  
Facility

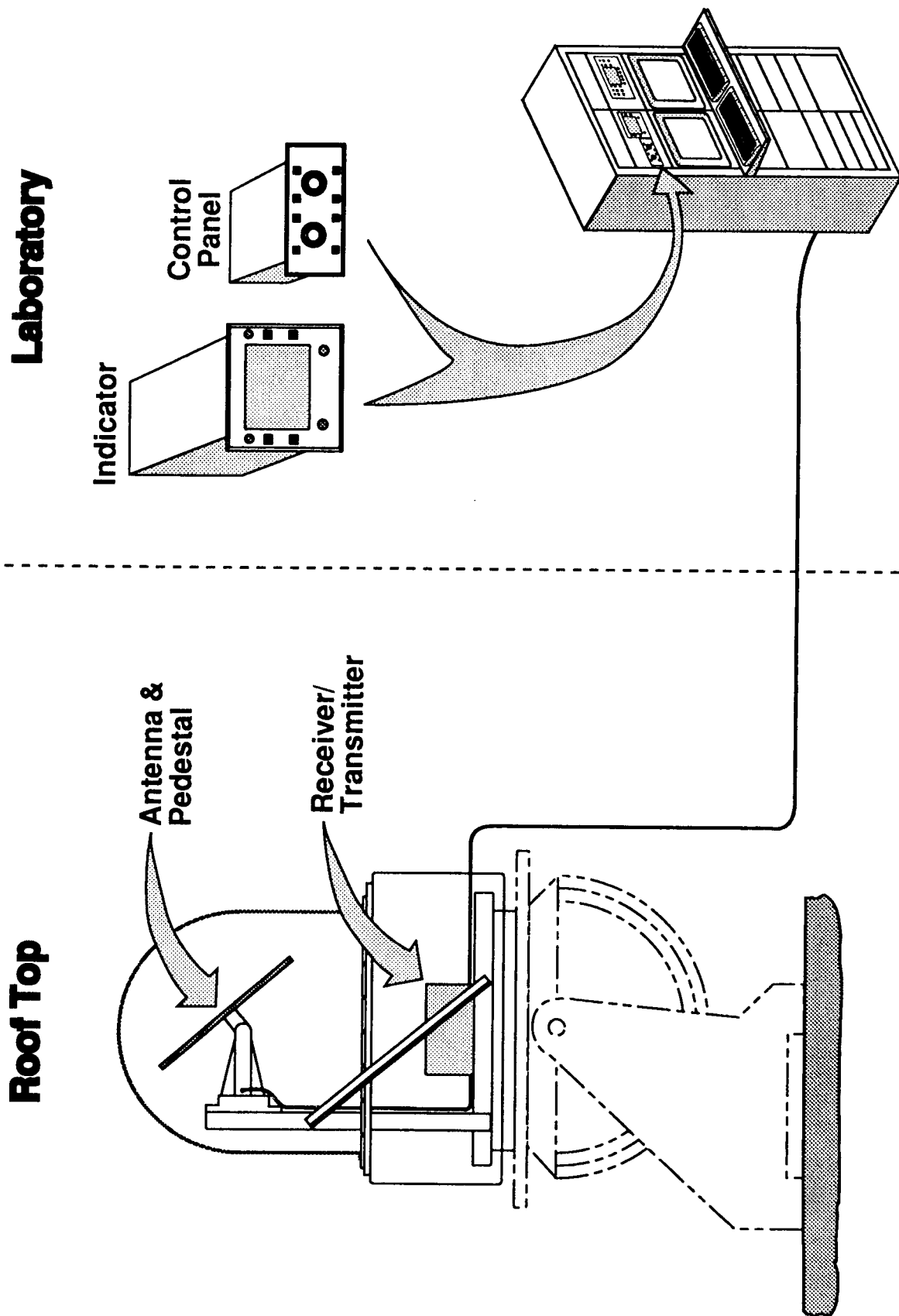
## Functional Diagram































# ROOF TOP RADAR FACILITY

W-S Radar System



# WINDSHEAR RADAR FLIGHT EXPERIMENT

- Sensor Procurement  
Std. W-X Radar  
Res. Radar Scat.  
Hi-power Mod. Kit
- Roof Top Radar  
Facility
- Antenna Pointing &  
Control Fixture
- Experiment Hardware  
Design & Build  
Test & Eval.
- Install Aboard 737 A/C
- Checkout Flights
- Data Collection  
Phase I  
Phase II  
Phase III

1988	1989	1990	1991	1992
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				
				

## **Session I. Airborne-Sensors**

Ramifications of the Recent FAA Rule for Wind Shear Systems on the  
Development of Forward-Looking Systems  
H. Patrick Adamson, TPS

527409

N91-11691

p17

RAMIFICATIONS OF THE RECENT FAA RULE  
FOR WINDSHEAR SYSTEMS  
ON THE  
DEVELOPMENT OF FORWARD-LOOKING SYSTEMS

H. Patrick Adamson  
Turbulence Prediction Systems  
Boulder, Colorado 80301

ABSTRACT

The recent FAA rule requiring windshear systems with flight guidance may have severe ramifications for the development of Infrared and other forward-looking systems. The industry needs to have and can have a more cost effective option through the use of a forward-looking system with a reactive backup instead of a reactive system with flight guidance. However, because of the short time for compliance with the new FAA rule, it is possible that existing transport aircraft will be in full compliance before a comprehensive investigation of all forward-looking systems can be completed. If this occurs, it is possible that the market for forward looking systems will be severely reduced, thereby eliminating the economic incentive to develop these much needed systems. Thus, to assure that this option is available for the airlines, it behooves the industry to immediately support an in-service evaluation of all available forward-looking systems.

PRESENTATION FOR THE  
SECOND COMBINED MANUFACTURER'S AND  
TECHNOLOGY AIRBORNE WIND SHEAR  
REVIEW MEETING

OCTOBER 18 - 20, 1988

"RAMIFICATIONS OF THE  
RECENT FAA RULE FOR WINDSHEAR SYSTEMS  
ON THE DEVELOPMENT OF  
FORWARD LOOKING SYSTEMS"

H. PATRICK ADAMSON

TURBULENCE PREDICTION SYSTEMS  
4876 STERLING DRIVE  
BOULDER, COLORADO 80301  
(303) 443-8157

## TURBULENCE PREDICTION SYSTEMS

### CURRENT FAA REQUIREMENT:

Airborne reactive Low Level Wind Shear system with flight guidance.

### AS AN INDUSTRY YOU NEED MORE OPTIONS...

#### ONE POSSIBLE OPTION:

An airborne reactive backup Low Level Wind Shear system with a TPS, airborne predictive Low Level Wind Shear and Clear Air Turbulence system.

i.e., Replace flight guidance with a predictive system capable of anticipating Low Level Wind Shear and Clear Air Turbulence.

#### ARE ANY PREDICTIVE SYSTEMS CURRENTLY CERTIFIED?

NO, a predictive air turbulence system has not yet been certified by the FAA.

#### ARE ANY PREDICTIVE SYSTEMS AVAILABLE FOR EVALUATION?

YES, Turbulence Prediction Systems has a system ready to evaluate in the commercial air transport sector now!

## TURBULENCE PREDICTION SYSTEMS - ADVANCE WARNING SYSTEM

### FEATURES:

Dual purpose system - LLWS and CAT

Meets industry standards proposed by SAE S7 sub-committee for a forward looking detection system.

Utilizes the industry standard Hazard Index (F Factor)

Meets military specifications

Bi-directional 429 ARINC buss i.e. capable of interfacing with current reactive Low Level Wind Shear systems

### WHAT IS REQUIRED TO EVALUATE THIS SYSTEM?

An in-service evaluation on a commercial air transport.

### IS THERE TIME TO EVALUATE THIS SYSTEM?

YES, TPS' system can be evaluated/certified within 1 year and can be available for installation during the 4th quarter of 1989.

WHAT ARE THE BENEFITS OF AN EVALUATION?

If successful, you will have increased safety with a cost-effective option.



## COST BENEFIT OF OPTIONS

Option A Airborne reactive Low Level Wind Shear system with flight guidance or

Option B Airborne reactive Low Level Wind Shear system and Turbulence Prediction Systems' Airborne predictive Low Level Wind Shear and Clear Air Turbulence system

<u>COST</u>	<u>Option A</u>	<u>Option B</u>
<b>Equipment</b>		
Reactive System	\$ 25,000.	\$ 25,000.
Flight Guidance	10,000.	
Predictive System		50,000.
Miscellaneous Materials	10,000.	15,000.
<b>Installation</b>		
Reactive System 125 hrs @ \$50/hr	6,250.	6,250.
Flight Guidance 125 hrs @ \$50/hr	6,250.	
Predictive System 125 hrs @ \$50/hr		6,250.
<b>Re-Certify</b>		
Flight Guidance 20 hrs @ \$100/hr	2,000.	0.
<b>Training</b>		
Simulator Modifications	20,000.	
Flight Guidance 4 hrs/person		
x 2 people/crew		
x 5 crews/aircraft		
x \$500 per hour	\$ 20,000.	\$ 0.
<b>Total Direct Cost per aircraft 1st yr</b>	<b>\$ 99,500.</b>	<b>\$102,500.</b>
<b>Down Time</b>		
Reactive System 125 hrs @ \$500/hr	62,500.	62,500.
Flight Guidance 125 hrs @ \$500/hr	62,500.	
Predictive System 125 hrs @ \$500/hr		62,500.
<b>Total Indirect Cost per aircraft 1st yr</b>	<b>\$125,000.</b>	<b>\$125,000.</b>
<b>Total Cost per aircraft 1st year</b>	<b>\$224,500.</b>	<b>\$227,500.</b>

### ANNUAL SAVINGS DUE TO CAT AVOIDANCE

\$14.25/flight* x 2,000 flights/yr	\$ 0.	\$ 28,500.
------------------------------------	-------	------------

\* Cost of CAT \$6.00/flight expressed in 1964 dollars "Report of the National Committee For Clear Air Turbulence"; U.S. Department of Commerce; December 1966, pp 37.

WHY SHOULD THE AVIATION INDUSTRY EVALUATE FORWARD  
LOOKING SENSORS NOW?

Once the existing fleet, i.e. retrofit, is in compliance with the mandated FAA windshear systems, it is very likely that forward looking sensors will not be required for these aircraft.

Thus, if the retrofit market is precluded as a potential market for a forward-looking sensor, there will be little, if any, economic incentive to begin or complete development of these forward-looking sensors for the balance of the potential market (i.e., approximately 300 new transports manufactured each year).

FOR AN UPDATE ON THE STATUS OF TPS,  
SYSTEM TESTS, SEE AIAA-88-4659 TITLED:

"AIRBORNE PASSIVE INFRARED SYSTEM FOR  
THE ADVANCE WARNING OF LOW-LEVEL  
WINDSHEAR AND CLEAR AIR TURBULENCE:  
1988 IN-SERVICE AND THEORETICAL WORK"

OR CONTACT:

TURBULENCE PREDICTION SYSTEMS  
4876 STERLING DRIVE  
BOULDER, COLORADO 80301

(303) 443-8157

TO INSURE THAT THERE IS A MARKET FOR FORWARD-LOOKING  
SENSORS, WHAT IS REQUIRED?

A SCHEDULED AIR CARRIER IS NEEDED TO JOIN WITH  
TPS AND OTHERS IN AN IN-SERVICE EVALUATION OF  
THIS ALTERNATIVE NOW!!

# AIAA'88

**AIAA-88-4659**

**Airborne Passive Infrared System for  
the Advance Warning of Low-Level  
Windshear and Clear Air Turbulence:  
1988 In-Service and Theoretical  
Work**

H. Patrick Adamson, Turbulence  
Prediction Systems, Boulder, CO

**AIAA/NASA/AFWAL Conference on  
Sensors and Measurements  
Techniques for Aeronautical  
Applications**

September 7-9, 1988/Atlanta, Georgia

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370 L'Enfant Promenade, S.W., Washington, D.C. 20024

AIRBORNE PASSIVE INFRARED SYSTEM FOR THE  
ADVANCE WARNING OF LOW-LEVEL WINDSHEAR AND CLEAR AIR TURBULENCE:  
1988 IN-SERVICE AND THEORETICAL WORK

H. PATRICK ADAMSON\*  
TURBULENCE PREDICTION SYSTEMS  
BOULDER, COLORADO

Abstract

Air turbulence is the leading cause of weather-related fatalities for commercial airlines. Air turbulence is classified as either Clear Air Turbulence (CAT) (high altitude) or Low-Level Wind Shear (LLWS) (low-altitude), which is the most dangerous. Currently, there is no method available to provide sufficient advance warning to the flight crew of either impending CAT or LLWS. Flight research, supported later by laboratory research and computer simulation, indicates that a micro-processor based passive infrared system could provide an adequate advance warning for both CAT and LLWS.

The effectiveness of this infrared system will be determined during an in-service evaluation on a commercial airline(s). This evaluation is scheduled to begin in September 1988 and to continue for up to 12 months. At that time, the system is expected to be certified by the Federal Aviation Administration and made available to the aviation industry. This system coupled with present avionic aids and pilot training will substantially reduce the probability of an accident due to air turbulence.

Introduction

As the leading cause of weather related air carrier accidents in the United States, air turbulence has been recognized as a national problem.<sup>1</sup> Consequently in 1987, the US government instituted an Integrated Wind Shear Program administered by the Federal Aviation Administration (FAA).<sup>2</sup> The airborne sensor segment of this program is jointly administered by FAA and NASA. The focus of this paper is to describe our work in assessing the effectiveness of an Infrared Remote Sensing System (Infrared) as a viable airborne sensor within this program.

Air Turbulence

Air turbulence is defined as the rapid change in the air/wind speed and/or direction that can have a dynamic

effect on the performance of an aircraft. Such turbulence has been classified as either Low-Level Wind Shear (LLWS) or Clear Air Turbulence (CAT), with LLWS presenting the most serious threat to aircraft and passenger safety.

Low-Level Wind Shear -

Low-Level wind shear is defined as air turbulence occurring between 1500 feet above ground level (AGL) and the surface. These events may be from 7 - 8 kilometers to 25 or 30 kilometers wide to thousands of meters high.<sup>3</sup>

"The meteorological phenomenon producing low-level windshear are, primarily, thunderstorms, gust fronts, fast-moving frontal zones, and less frequently, low-level inversions."<sup>3</sup> "The most threatening types of wind shears are downbursts, or microbursts - descending shafts of air..."<sup>4</sup> Microburst lifecycles are typically 10 - 15 minutes.

Clear Air Turbulence -

"Clear air turbulence, often termed CAT, is a region of high turbulence encountered by an aircraft without visual or radar warning. CAT includes all forms of turbulence occurring in clear air which does not involve convective forces."<sup>5</sup>

"Two separate conditions are known which result in CAT. The first condition is created by a standing wave found in the lee of a mountain barrier which occurs when statically stable air is carried over the mountains. The second condition results from waves formed in statically stable layers in the atmosphere that are subjected to sufficiently strong vertical wind gradient (shear)"<sup>6</sup>

Airborne Sensors/Systems - LLWS

There are two basic types of airborne sensors/systems used for detecting impending LLWS; they are reactive and predictive. To ascertain the danger to the aircraft from air turbulence, a number of factors must be considered. Since these factors can occur in different combinations, a hazard

\*Principal Investigator

index is used to ascertain the extent of the danger to the aircraft. Both systems need to characterize the hazard to the aircraft. One accepted formula to calculate this hazard is:

$$\frac{WX}{g} - \frac{V}{AS} = \text{Hazard Index}$$

- A positive (+) number represents a hazard.
- $\frac{WX}{g}$  is the rate of change in horizontal winds in knots per second and a positive (+) number indicates a tailwind.
- $g$  equals the gravitational constant of 19.04 knots per second.
- $V$  equals vertical wind velocity in knots and a minus (-) number indicates a downdraft.
- $AS$  equals airspeed in knots.

#### Reactive (In-Situ) Systems -

These systems utilize the aircraft as the sensor to ascertain when the aircraft is entering wind shear. At this point, immediate action is required by the flight crew to escape the event.

#### Predictive (Forward Looking) Systems, LLWS -

These systems are comprised of any sensor(s) that would provide advance warning to the flight crew of impending windshear. If the warning is provided more than five miles (approximately 1.5 minutes) before the aircraft would encounter the LLWS, the warning is classified as "advisory". Less than five miles, it is an "executive" warning. An executive warning indicates that immediate action must be taken by the flight crew to avoid encountering LLWS.

Airborne microwave doppler, laser doppler (LIDAR) and infrared techniques have been and are currently being tested to ascertain their effectiveness in providing advance warning of impending LLWS.

#### Airborne Sensors/Systems - CAT

Since encountering CAT has not traditionally been considered a crisis event, no effort has been conducted to develop a reactive CAT system. However, because of the inconvenience and cost associated with CAT, various techniques have been tested for the purpose of providing advance warning of impending CAT. Other than Infrared, none have been considered successful.

#### Infrared Application - LLWS

The application of Infrared to provide advance warning of air turbulence is based upon meteorological dynamics which causes the event. Based on meteorological research conducted by Byers and Braham<sup>6</sup> in their Thunderstorm Project and research conducted by Fawbush and Miller<sup>7</sup> which demonstrated that down drafts (microbursts) were colder than the surrounding air, Drs. Peter Kuhn and Fernando Caracena<sup>8</sup> concluded that infrared technology could be used to detect these cold downbursts.

This hypothesis was subsequently substantiated by airborne research conducted by Dr. Kuhn in the Joint Airport Weather Study (JAWS).<sup>9</sup> During the study, 42 microbursts were penetrated at altitudes of 300 - 800 feet AGL with 100% success in advance identification of these events. Later flights proved that infrared will function properly in light rain and dry air.<sup>9</sup>

An analysis of this research and other studies enable us to ascertain, from perceived temperatures, an estimation of the wind velocities that the aircraft is expected to encounter. Thus, the extent of the impending danger to the aircraft can be estimated through the use of infrared technology.

#### Infrared Application - CAT

Although others had, with limited success, used infrared to detect CAT, Dr. Kuhn conducted the most extensive and successful program from 1978 through 1982. In approximately 700 flight hours, he obtained a 98% success rate in detecting CAT with advance warning ranging from 2 to 9 minutes.<sup>10</sup>

#### Infrared Current Status

As an extension of the instrument design and development work conducted at the Instrument Development Laboratory at the University of Colorado, we have developed an airborne passive infrared system that provides advance warning of both LLWS and CAT. This system is now in the pre-production phase ready for aircraft installation. The system meets military specifications. It weighs approximately 30 pounds and the dimensions are 11 1/4" X 8 1/2" X 6 1/2". The production model, on which construction has begun, is approximately 2/3 of the weight and size of the pre-production model.

To validate the performance of the pre-production instrument, the following are in progress:

- 1) Laboratory simulations
- 2) Computer simulation
- 3) In-service evaluation

#### Laboratory Simulation - LLWS

The purpose of the laboratory simulation is to establish the accuracy, sensitivity and reliability of the instrument. To accomplish this, a test facility has been constructed to simulate atmospheric conditions. This facility allows for the calibration and the testing of the instrument at various temperatures to detect varying temperatures at both near and far distances. These tests assess the system's capacity to detect small change in temperatures at various distances and to reliably repeat these tests.

Since the functions of the optical and mechanical components are controlled by a microprocessor, the software must also be tested for accuracy and reliability. In addition, the instrument must be tested for suitability in an aircraft environment.

#### Laboratory Simulation - CAT

Based on the in-flight research conducted by Dr. Kuhn, we do not anticipate that CAT simulation will be necessary. However, depending on the results obtained in the in-service evaluation phase, CAT simulation could be conducted later.

#### Computer Simulation - LLWS

The purpose of these simulations is to simulate flying our instrument through NASA generated microburst weather models. This involves selecting 1) an atmospheric model, 2) a particular look distance (calculate infrared transmittance), and 3) a flight path (landing or takeoff). These parameters are used to calculate the expected hazard index.

These atmospheric models include a complete thermodynamic profile of the event in the spatial realm of five kilometers on either side of the event and four kilometers in altitude. That is, the model provides temperatures, pressure, rain, water vapor, snow, and vertical/horizontal wind profiles.<sup>11</sup>

NASA has generated two models that they consider represent the conditions contained in a microburst. These are the "Wet" and "Dry" models.

These axisymmetric models, by design, include the most extreme atmospheric conditions that an aircraft could be expected to encounter. That is, they range from the wettest to the driest microburst with cold or warm downdrafts.

The Wet model includes rainfall of approximately 4.5 inches per hour at the center of the microburst and has a decreasing temperature profile, i.e. a cold downdraft relative to the ambient air. The rain rate and temperature profile approximate the conditions encountered by Delta 191 at Dallas in 1985. This model appears to accurately represent meteorological conditions as observed by in-flight researchers as well as reported by aircraft digital flight data recorders.

The Dry model does not include any precipitation and has a cold downdraft that becomes warmer near ground level. While some ground based research indicates neutral or positive temperatures for the radial winds associated with microbursts, empirical airborne research data supports only decreasing temperature profiles. For example, in JAWS only decreasing temperatures were recorded in all 42 microbursts that were penetrated at 300' to 800' AGL.<sup>8</sup> Furthermore, almost all of these were dry microbursts. To our knowledge, the only increasing temperatures recorded to date in a microburst were from ground measurements.<sup>12, 13</sup> The problem with ground based data, however, is the measurement can be affected by the warm air next to the ground.

#### Computer Simulation Procedures - LLWS

##### Infrared Transmittance Calculations -

To calculate the effective look distance of the instrument, transmittance of infrared power in the atmospheric conditions presented in the model must be calculated. The LOWTRAN 6 computer program is used for this purpose. This program was developed by the Air Force Geophysics Lab (AFGL) and is the standard used by the infrared industry.<sup>14</sup>

##### Aircraft Flight Path -

The model assumes a normal landing and takeoff pattern for a typical air transport. For each simulation, the flight profile is determined first. For landing, the aircraft flies horizontally from 10km to within 3.6km of the microburst's axis at an altitude of 300 meters AGL. At this point, which is the



outer edge of the microburst, the aircraft descends at a 3 degree glide slope through the microburst and lands 2 km beyond the microburst axis.

For takeoff, the aircraft remains on the ground during the simulation with the planned rotation point located at the near edge of the microburst.

After the flight pattern is established, the next step is to determine the hazard by establishing the vertical and radial winds that will be encountered.

#### Hazard Index -

Two separate hazard indices are calculated. One is the hazard index computed by the system (system's index) using proprietary algorithms and the other is the hazard index computed using inertial data (inertial index). By including data from the inertial index, it is possible to assess the accuracy of the system.

The system index is computed by using LOWTRAN 6 to calculate the transmission of infrared power along the proposed flight path. The power is calculated on the spatial grid by an analytic expression. Once the total power is computed, the perceived temperature can be calculated. Assuming an air speed and knowing the change in perceived temperature, vertical and horizontal winds can be inferred and thus, the hazard index is determined.

The inertial index is computed from inertial data experienced by the aircraft. That is, the rate of change in horizontal winds, vertical winds and air speed. The formula to calculate this index is:

$$\dot{W}_X/g - V/AS = \text{hazard index.}$$

The process of calculating both the system index and the inertial index involves flying a normal takeoff or landing profile into a specific microburst model and then calculating, at one second intervals, the specific hazard index. By time tagging each index (system and inertial) the system index at a given point in time can be compared to the inertial index that the aircraft would encounter seconds later. This comparison provides the opportunity to assess the accuracy of the system index.

#### Computer Simulation Results - LLWS

##### Wet Cold Microburst -

In the landing profile, depicted in Figure 1, the system, using a hazard

index alert of 0.15, would have provided a warning 33 seconds prior to that provided by the inertial index. That is, the inertial index exceeded 0.15 alert level, approximately 33 seconds after the system index exceeded 0.15. At .125 the warning would have been approximately 40 seconds.

Warning time can be determined by counting the number of boxes that occur after the instrument line crosses the alert line (0.15) to the point where the pluses (+) cross the alert line (0.15). Each box or plus (+) equals one second. The selection of 0.15 for an alert level is based on assumed levels of aircraft performance. The level could be set either higher or lower. The problem with high settings is the danger of encountering a dangerous microburst without providing a warning. A low setting however, may result in a warning when the air turbulence is not dangerous (nuisance alert). This is one of the answers the in-service evaluation will provide.

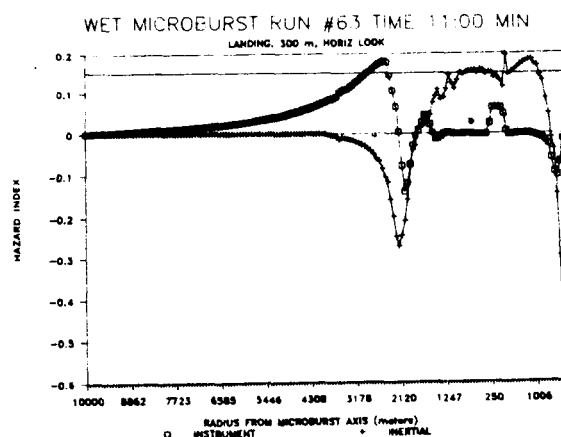


Figure 1

In the takeoff profile, depicted in Figure 2, the system, using an alert level of 0.15, would not have provided an advance warning, but at .125 it would have provided a warning approximately 13 seconds prior to that provided by the inertial index.

When it is determined, by all parties involved, that the system is operating properly, two more systems will be installed and evaluated by all parties for up to 12 months. The FAA has expressed an interest in the analysis of this data and it is anticipated that the data obtained from this in-service evaluation will be a significant factor in obtaining FAA certification.

### Conclusion

Assuming the successful completion of the in-service evaluation, we expect that this AWS will be available to the aviation industry by the later part of 1989. With the availability of an advance warning system coupled with a reactive system and continued pilot training, the probability of avoiding a LLWS accident is almost 100%.

We are looking forward to making continued progress in assisting the aviation industry in increasing aviation safety.

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- <sup>2</sup>Federal Aviation Administration, "Integrated FAA Wind Shear Program Plan," United States Department of Transportation, DOT/FAA/DL-87/s, April 1987.
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- <sup>5</sup>Kuhn, Peter M., Inventor, "Method and Apparatus for Detecting Clear Air Turbulence"; United States Patent; 4,266,130, May 5, 1981, p. 1.
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- <sup>9</sup>Sinclair, P. and P. Kuhn, "Forward Looking Airborne Infrared Wind Shear Sensor Operations in Precipitation," Paper NOAA #43-RANR-5-03966, October 1987.
- <sup>10</sup>Stearns, L. and V. Nogay, "Final Statistical Report on Aviation Safety Technology (In-Flight Detection and Prediction of Clear Air Turbulence," NASA, Ames Research Center, RTOP 505-08-11, RNA-43115-B, December 1979.
- <sup>11</sup>Proctor, F., S. Chuang, J.W. Zack, M.L. Kaplan, and F. Proctor, "A Numerical Weather Prediction System Designed to Simulate Atmospheric Downburst Phenomena," AIAA-84-0352.
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- <sup>13</sup>Fujita, T., The Downburst---Microburst and Macrobust, Mesometeorology Research Project, SMRP Dept. of Geophysics Sciences, University of Chicago, 1985.
- <sup>14</sup>Kneizys, F.X., et.al, "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 6," Air Force Geophysics Laboratory, AFGL-TR-83-0187, August 1983.

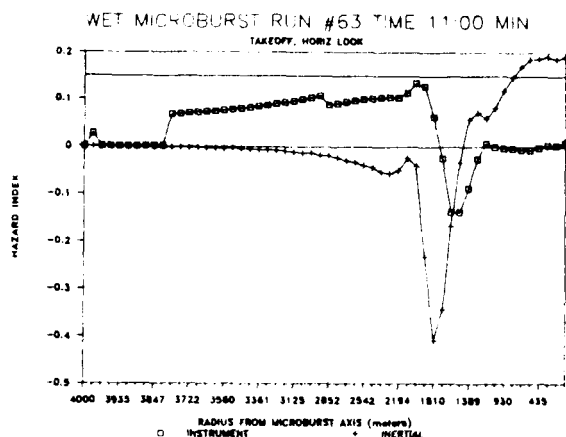


Figure 2

#### Dry Hot Microburst -

In this NASA provided model, in neither the landing nor takeoff profile did the system index provide a warning earlier than the inertial index. This would always be the situation because the system index is based on encountering a cold downburst in either the wet or dry microburst.

#### Dry Cold Microburst -

In order to assess the accuracy of the instrument in the dry microburst model, we combined the Dry microburst model with the cold temperature profile (decreasing temperature) of the wet microburst model. This temperature profile is representative of the airborne temperature changes recorded for the dry microbursts encountered in the JAWS program.

In the landing profile, depicted in Figure 3, the system index, using an alert level of 0.15, would have provided a warning approximately 27 seconds prior to that provided by the inertial index.

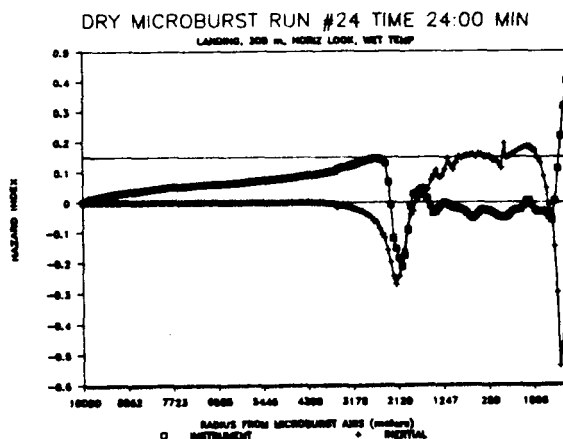


Figure 3

In the takeoff profile, depicted in Figure 4, the system index, using an alert level of 0.15, would have provided a warning approximately 39 seconds prior to that provided by the inertial index.

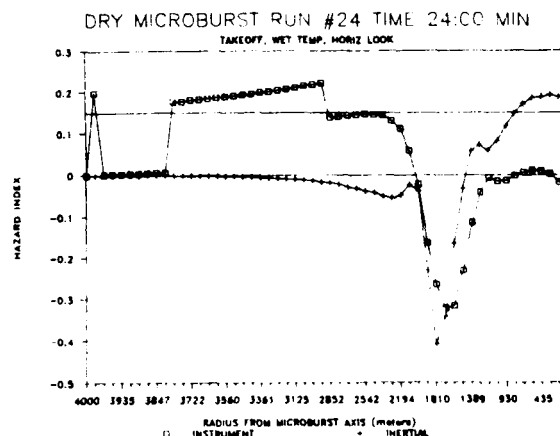


Figure 4

#### Actual Flight Data -

While computer simulations and modelling are excellent analytical tools, it is desirable to use real data whenever possible. Consequently, we have taken the actual flight data from several flights: Delta 191, Iberia 933 (Logan) and an incident occurring over Atlanta, and simulated what warning, if any, the system index would provide at an alert level of 0.15. In each situation, the actual hazard encountered coincided closely with the system hazard index. For example, in the Delta 191 accident the system index set at 0.15 alert level would have provided a 30 second advance warning in the landing profile.

#### In-Service Evaluation -

In conjunction with Sperry Commercial Flight Systems, a division of Honeywell, Inc., we will conduct an in-service evaluation of our system for advance warning of CAT and LLWS. This advance warning system (AWS) will be installed with a dedicated flight recorder and a Honeywell reactive system.

This evaluation will be conducted in two phases. The first phase, involving one system, will be flown either on a commercial airline or a corporate aircraft for a period of at least 30 days.

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## **Session I. Airborne Sensors**

**Status of the Delco Systems Operations Forward Looking Wind Shear  
Detection Program  
Brian Gallagher, Delco Systems**

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STATUS OF THE DELCO SYSTEMS OPERATIONS

FORWARD LOOKING WINDSHEAR DETECTION PROGRAM

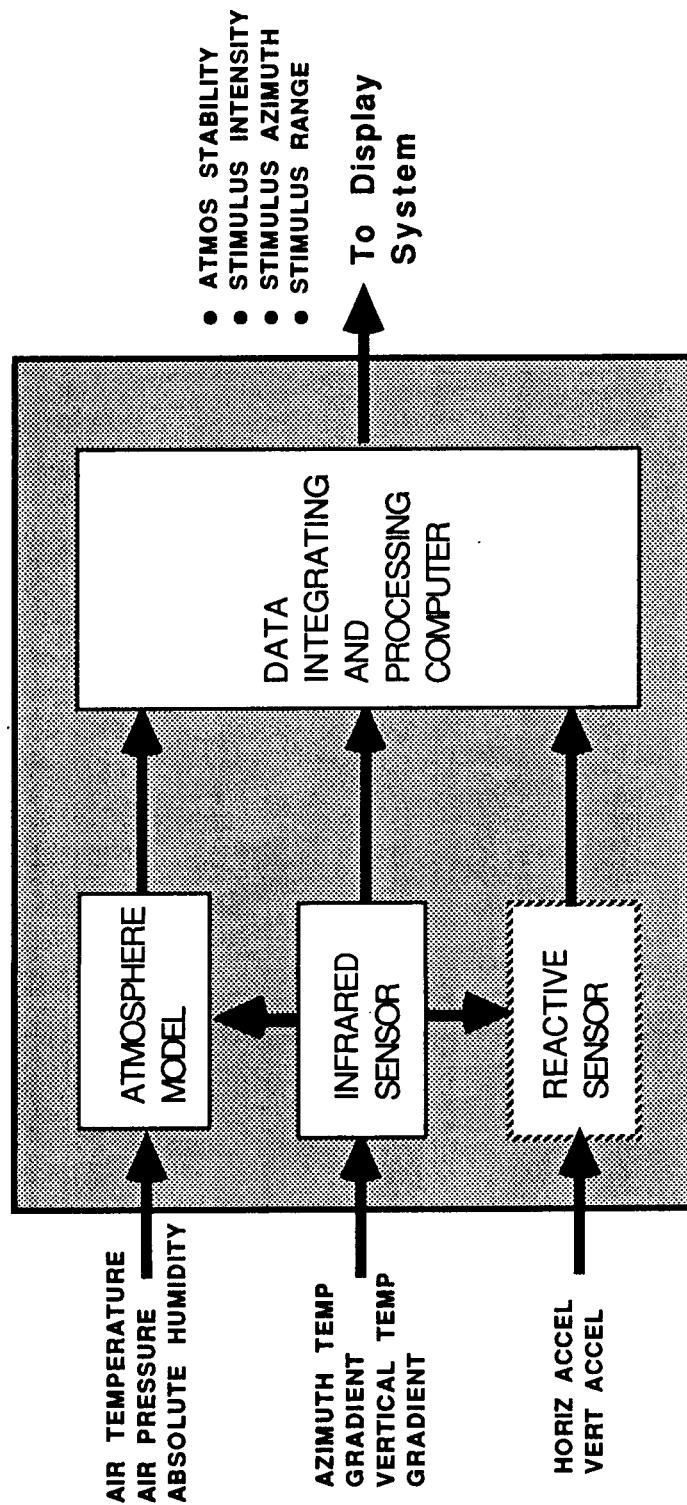
Brian J. Gallagher  
Delco Systems Operations  
Milwaukee, Wisconsin 53201

ABSTRACT

Delco Systems Operations, a division of General Motors Hughes Electronics Corporation, is developing a Forward Looking Windshear Detection System based on the integration of infrared remote sensing and accelerometer reactive sensing technologies. The IR sensor is a multi-spectral, scanning radiometer operating in the 8 to 14 micron region. A 2 x 5 detector array with parallel-serial scanning produces 60 degrees horizontal and 10 degrees vertical-fields of view. Using multiple wavelength signals, azimuth temperature gradients are analysed for characteristic signatures of thermally induced windshear phenomena. Elevation temperature gradients are processed through an atmosphere model to continuously compute a stability index for arming microburst detection criteria. The atmosphere model and proprietary computer processing algorithms combine to generate coarse estimates of disturbance ranges based on multiple wavelength radiance data with different extinction coefficients. Computer outputs of atmospheric stability, disturbance intensity, and azimuth and range information provide a situation display capability. A ground operated, experimental radiometer has been developed and is being used to verify our detection and discrimination concepts at an atmospheric and simulated rain test facility in Milwaukee. A prototype airborne radiometer is being developed for flight test evaluation during the summer of 1989.

## DELCO SYSTEMS OPERATIONS

### FORWARD LOOKING WINDSHEAR DETECTION SYSTEM



System Functional Diagram

## DELCO SYSTEMS OPERATIONS

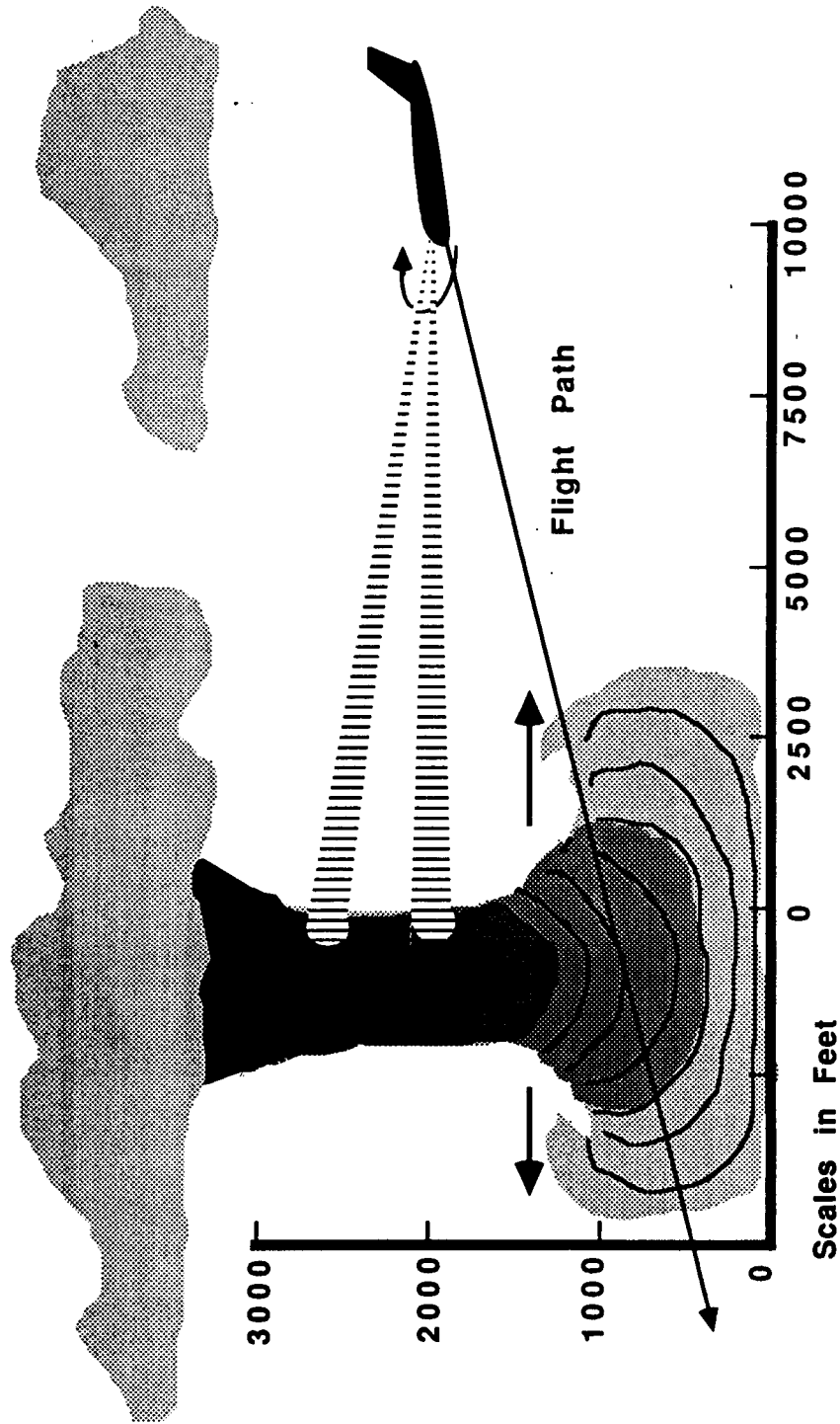
### FORWARD LOOKING WINDSHEAR DETECTION SYSTEM

#### INFRARED SENSOR

- Passive, Multi-spectral, Scanning Radiometer
  - Far IR Spectral Region (8 - 14 microns)
  - 2 x 5 Detector Array
  - Parallel-Serial Scanning
  - Sliding, 3/5 Operating Wavelengths
  - 60° Horizontal Field of View
  - 10° Vertical Field of View
- Volume: < 200 cubic inches
- Weight: < 10 pounds
- Power: < 100 watts

## DELCO SYSTEMS OPERATIONS

### FORWARD LOOKING WINDSHEAR DETECTION SYSTEM

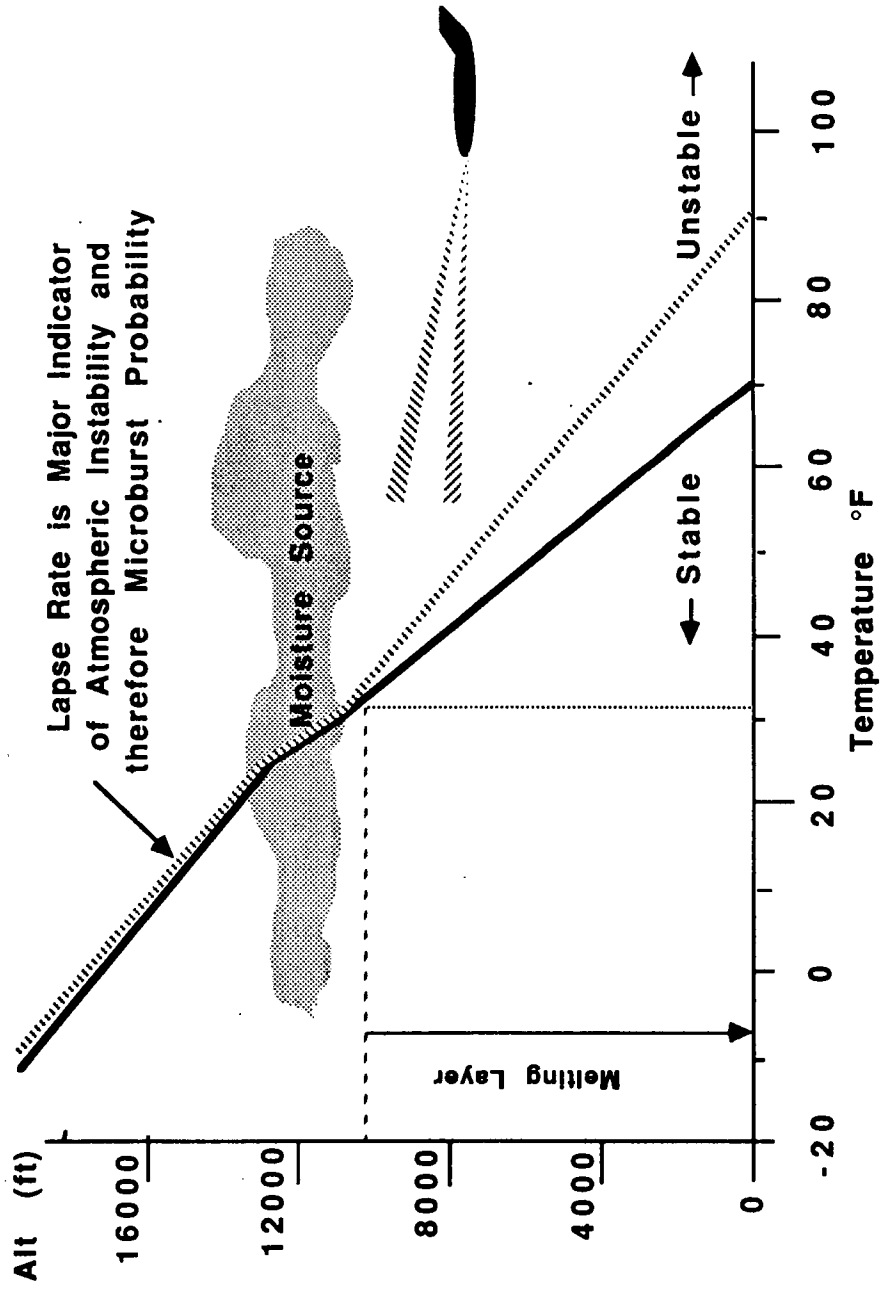


### Infrared Detection of Microbursts



## DELCO SYSTEMS OPERATIONS

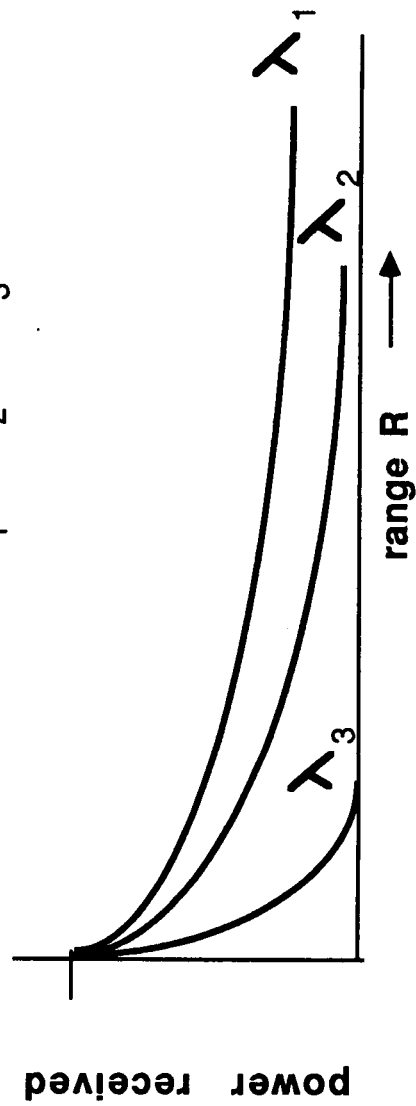
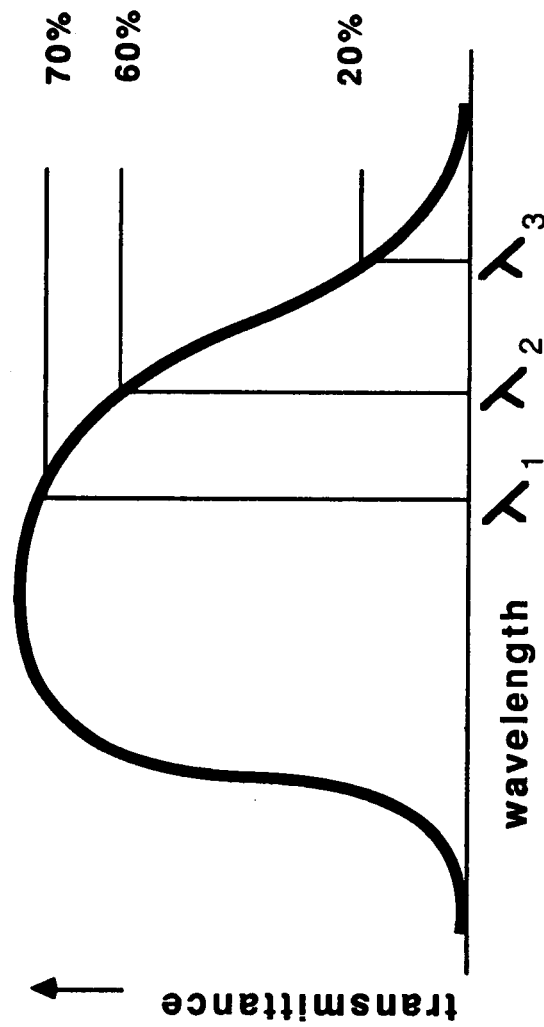
### FORWARD LOOKING WINDSHEAR DETECTION SYSTEM



### Lapse Rate and Atmospheric Stability

## DELCO SYSTEMS OPERATIONS

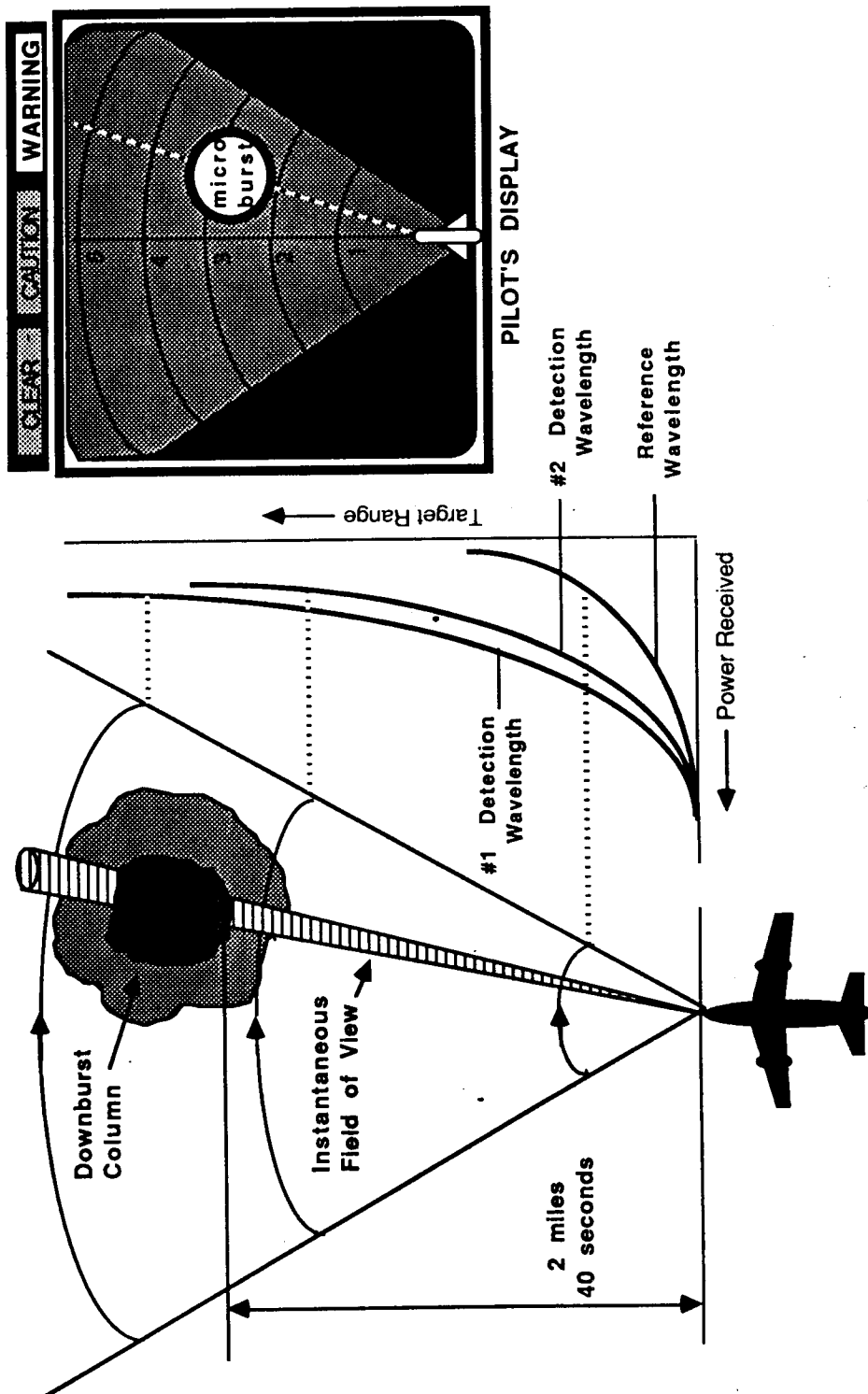
### FORWARD LOOKING WINDSHEAR DETECTION SYSTEM



Range Sensitivity of Operating Wavelength

## DELCO SYSTEMS OPERATIONS

### FORWARD LOOKING WINDSHEAR DETECTION SYSTEM



### Detection and Display System Operation

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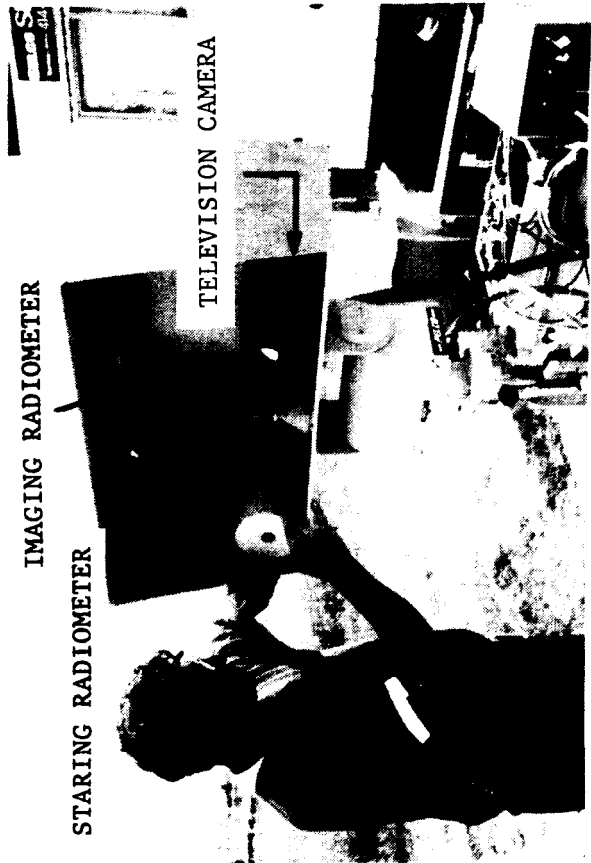


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IMAGING RADIOMETER

STARING RADIOMETER

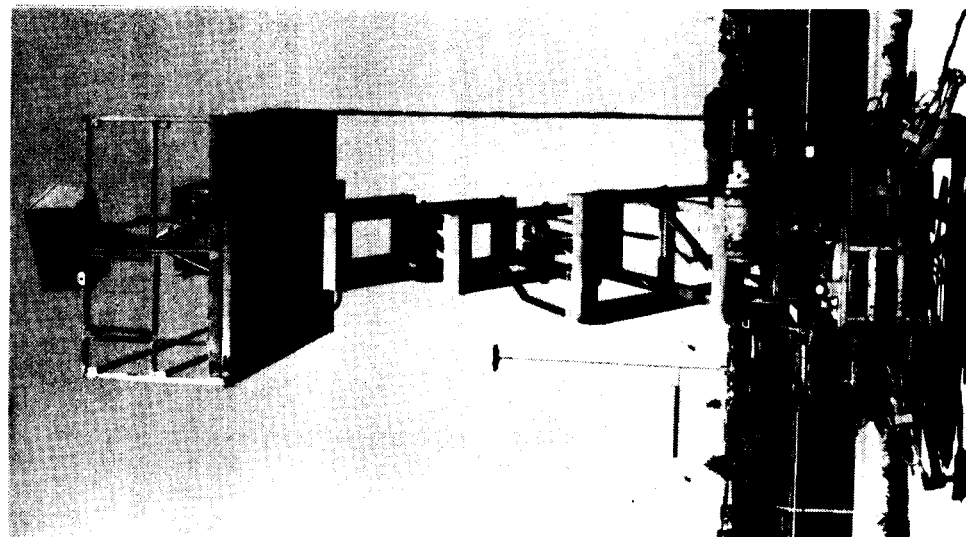


TELEVISION CAMERA



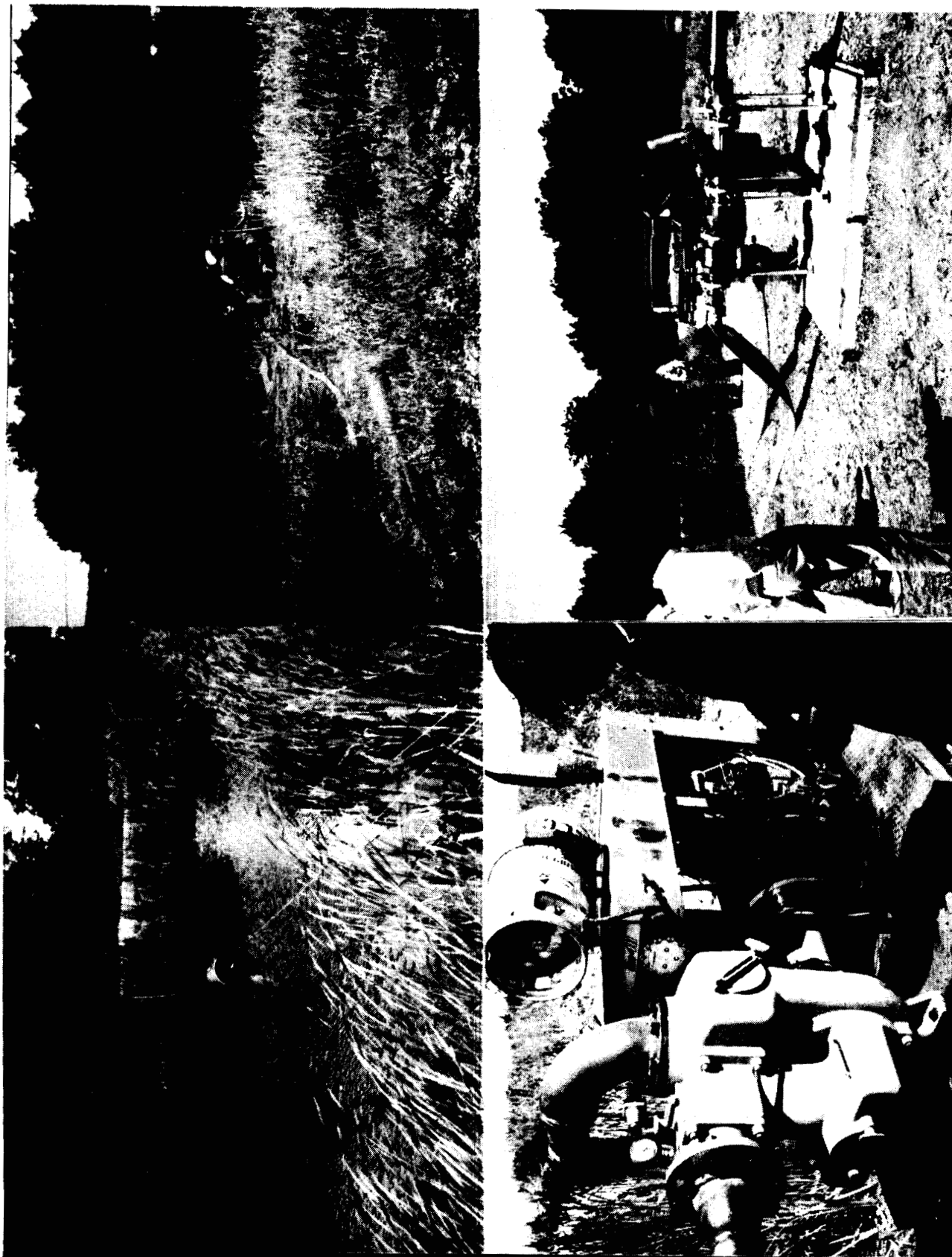
EXPERIMENTAL RADIOMETER TEST SETUP

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SPRAY SYSTEM, EXPERIMENTAL RADIOMETER,  
& EQUIPMENT TRAILER

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PUMPING AND CONTROLS SYSTEM

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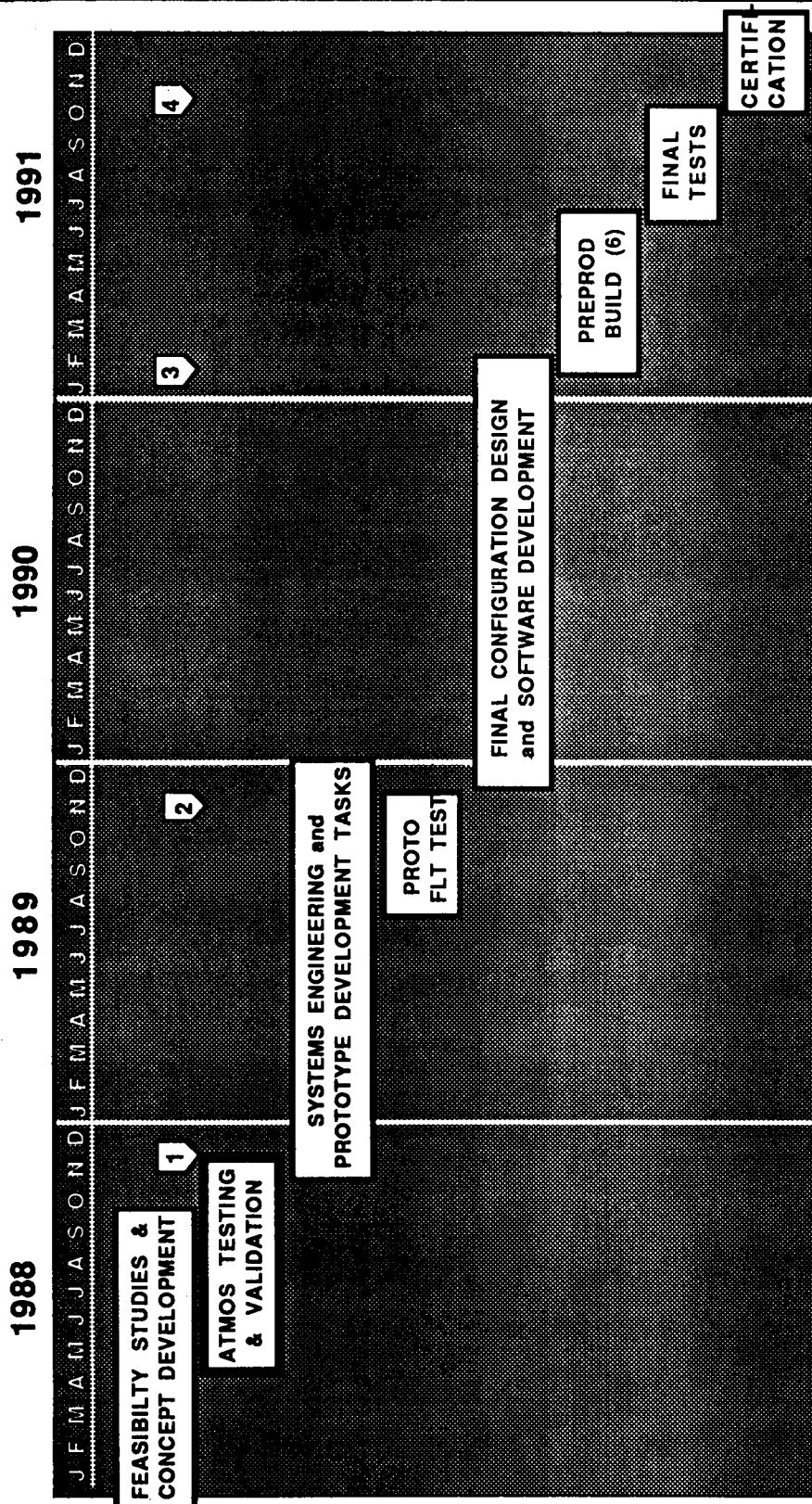


SPRAY SYSTEM IN OPERATION



# DELCO SYSTEMS OPERATIONS

## FORWARD LOOKING WINDSHEAR DETECTION PROGRAM



### Program Schedule

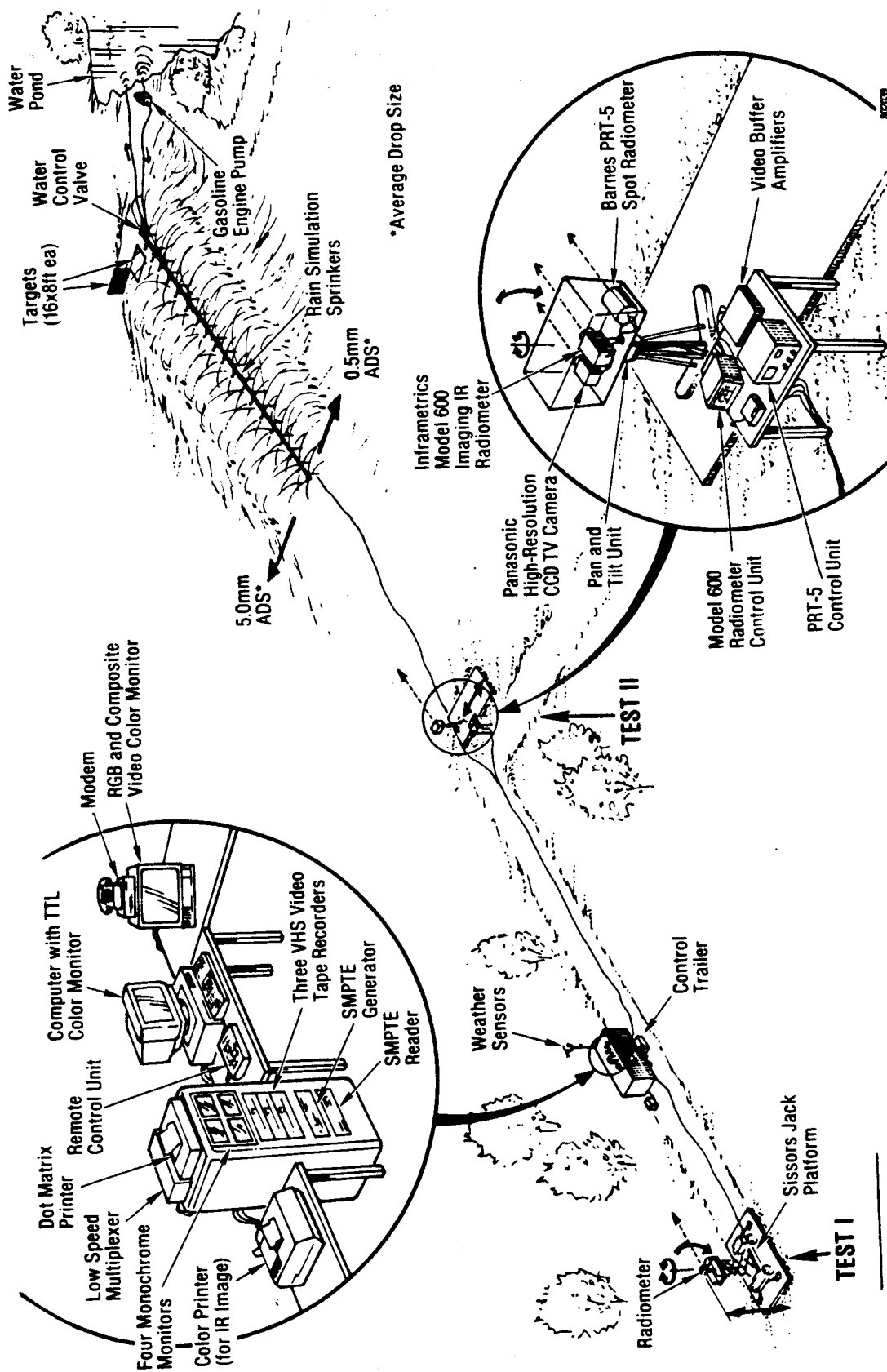
## DELCO SYSTEMS OPERATIONS

### FORWARD LOOKING WINDSHEAR DETECTION SYSTEM

#### STATUS

- FEASIBILITY STUDY COMPLETE
- ATMOSPHERIC TESTING PROGRAM
  - Data Collection completed
  - Data Analysis in Progress
- PROTOTYPE SYSTEM DEVELOPMENT
  - Airborne IR Sensor to be flight tested summer 1989

# WIND SHEAR TEST SETUP



Delco Systems  
Operations

## **Session I. Airborne Sensors**

**Infrared Thermal Imaging of Atmospheric Turbulence**  
David Watt and John McHugh, University of New Hampshire  
William Pfeil, Kollsman

527411

N91-11693

INFRARED THERMAL IMAGING OF ATMOSPHERIC TUBULENCE

pls

David Watt and John McHugh  
University of New Hampshire  
Durham, NH 03824  
William Pfeil  
Kollsman  
Merrimack, NH 03054

ABSTRACT

A technique for analyzing infrared atmospheric images to obtain cross-wind measurements is presented. The technique is based on Taylor's frozen turbulence hypothesis and uses cross-correlation of successive images to obtain a measure of the cross-wind velocity in a localized focal region. The technique is appealing because it can possibly be combined with other IR forward look capabilities and may provide information about turbulence intensity. The paper describes the current research effort, its theoretical basis, and its applicability to wind shear detection.

Image Cross-Correlation for  
Atmospheric Wind Measurement:  
Review of Work in Progress

David Watt  
John McHugh  
Department of Mechanical Engineering  
The University of New Hampshire  
Durham, N.H.

William Pfeil  
Kollsman Instrument Co.  
Merrimack, N. H.

## GOALS

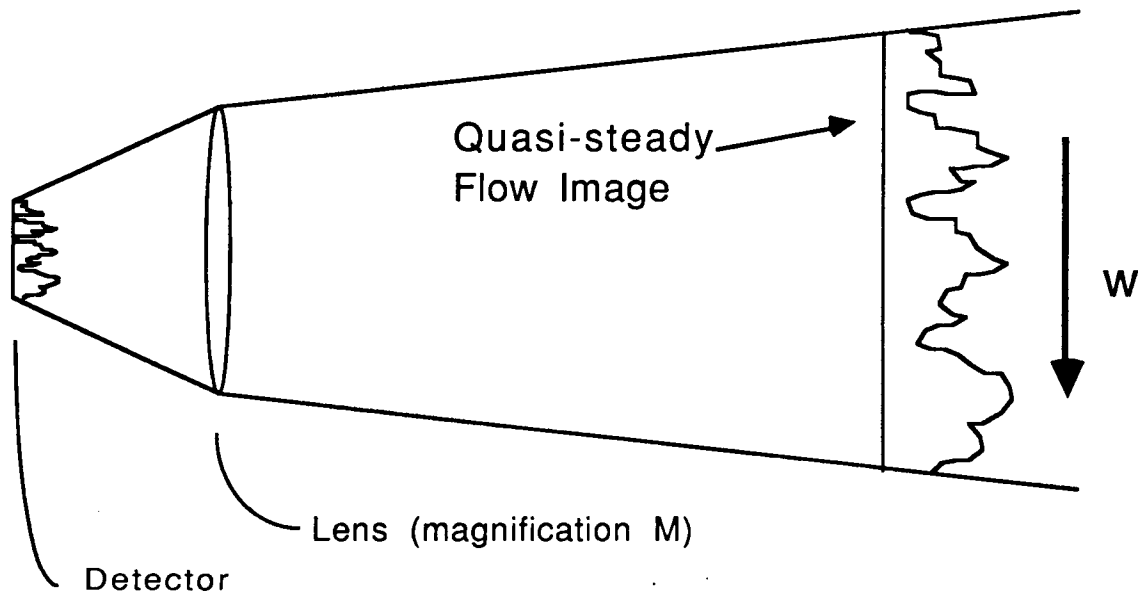
Primary goal is to develop a predictive on-board windshear detection device

The desired specifications of a future detection system include

1. Capable of detecting 1-2 kilometers ahead of plane
2. Capable of obtaining some measure of the NASA/FAA hazard index.
3. Monitor crosswind by image analysis.

# APPROACH

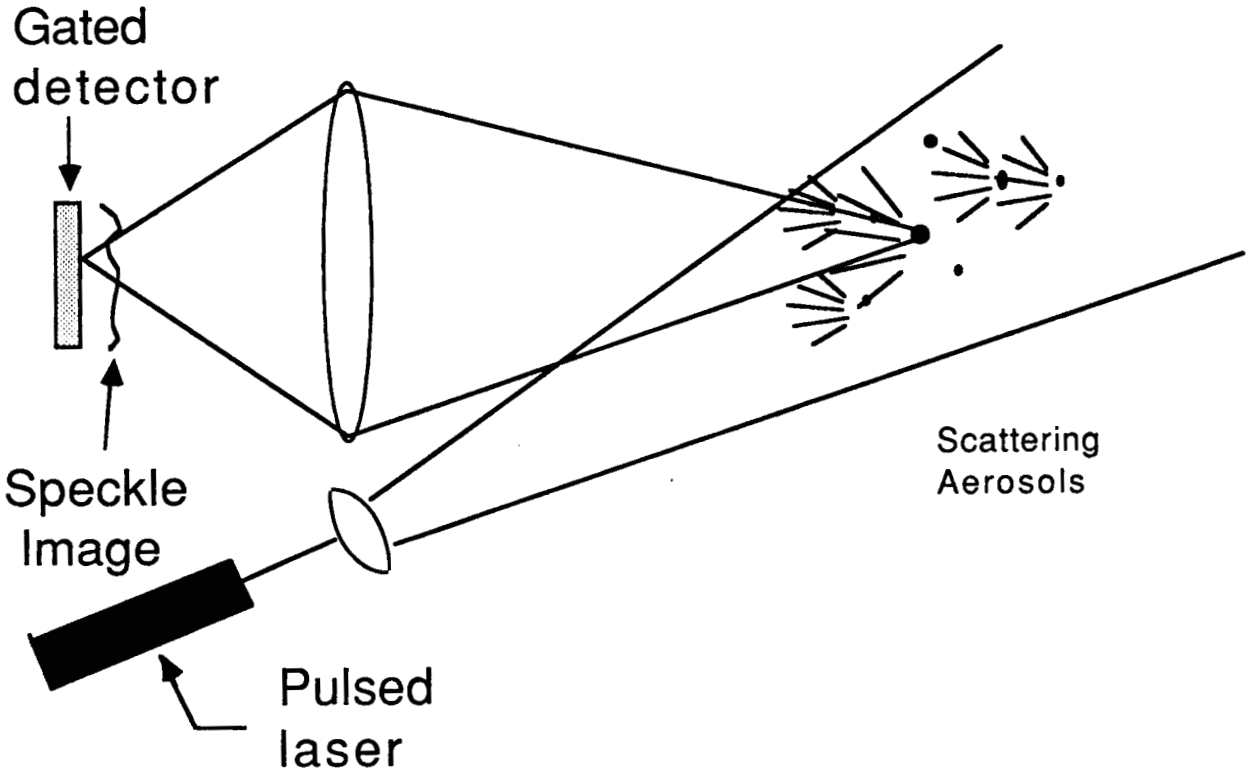
## Image Cross-correlation Velocimetry



- Taylor's "Frozen Turbulence" Assumption:
  - 1) Flow image moves at dominant velocity scale.
  - 2) Fine scales change slowly, Flow image steady
- Velocity determined comparing two successive images within short time interval.
- Comparison mechanism is cross correlation function.
- Continuously monitor cross-wind velocity.
- Images generated by various optical phenomena.



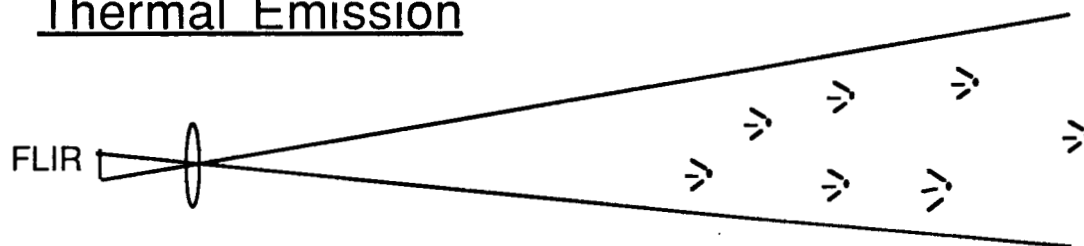
# Laser Speckle



- \* Speckle is coherence artifact
- \* Steady Scattering and Refractive Index Field
- \* Requires laser & gated detector for ranging
- \* Ranging by time of flight during gating interval
- \* Could be integrated with lidar

## Quasi-Steady Turbulence Generated Images (cont'd)

### Thermal Emission



-Passive Detection

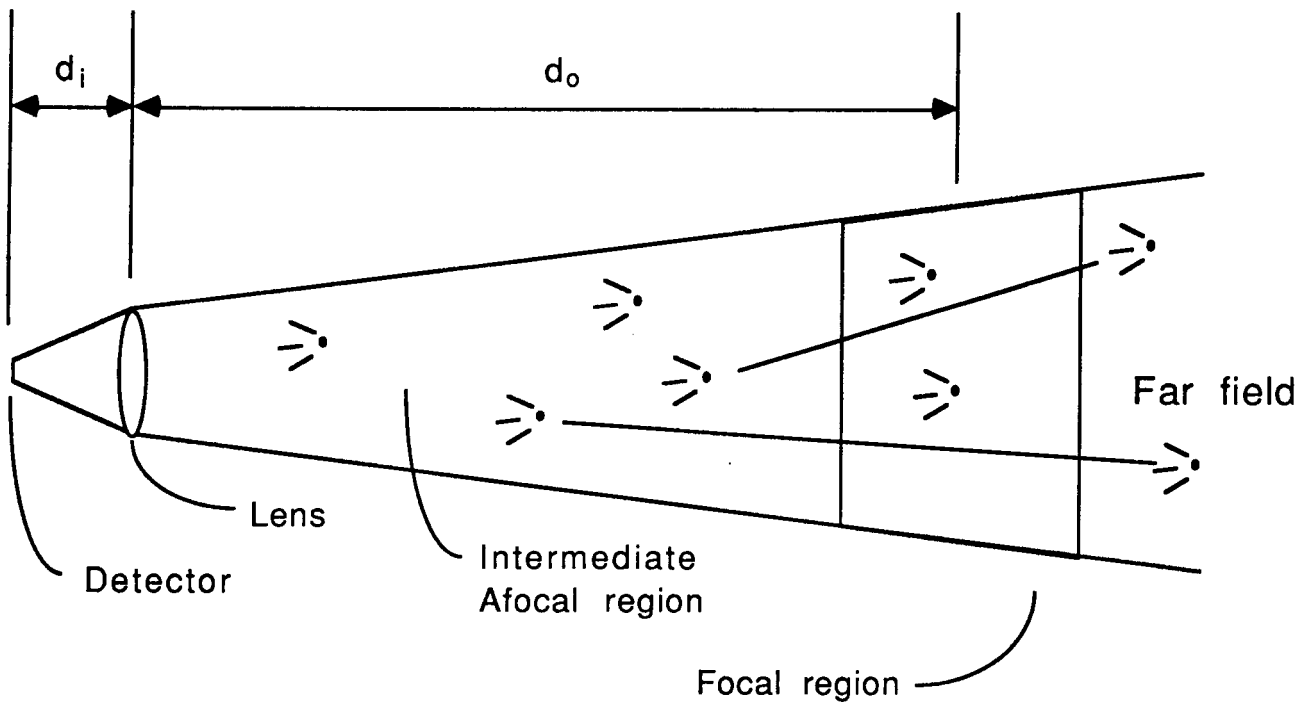
-IR intensity variation driven  
by temperature fluctuations

-Images may provide other relevant information:  
Turbulence Intensity  
Temperature gradient

-Compatible with other aircraft  
forward-look needs

-Signal strength to be evaluated in detection region

# Passive IR Imaging In Absorbing-Emitting Media



Need to Isolate Focal Region

Far-field signal attenuated by atmospheric absorption

Signal from intermediate range is defocused.

# Imaging Model

## Radiative Transfer Equation

$$N = \int_v \int_z \int_\omega B(\omega, T) \phi(v) \frac{\partial \tau(v, z)}{\partial z} dz d\omega dv$$

$B(\omega, T)$  = Emitted and incident radiation

$\phi(v)$  = Spectral transmittance of lens.

$\frac{\partial \tau(v, z)}{\partial z}$  = Differential transmittance of atmosphere.

$\omega$  = Solid angle

$N$  = Radiant flux onto detector pupil

## Model Imaging Equation

$$i(x, y) = \iiint_{\omega(x, y, z)} h(x, y, z) * \underbrace{(\epsilon e_{b, \lambda}(x, y, z) \exp(-\alpha z))}_{\text{Model RTE}} dx dy dz$$

$h$  - point spread function

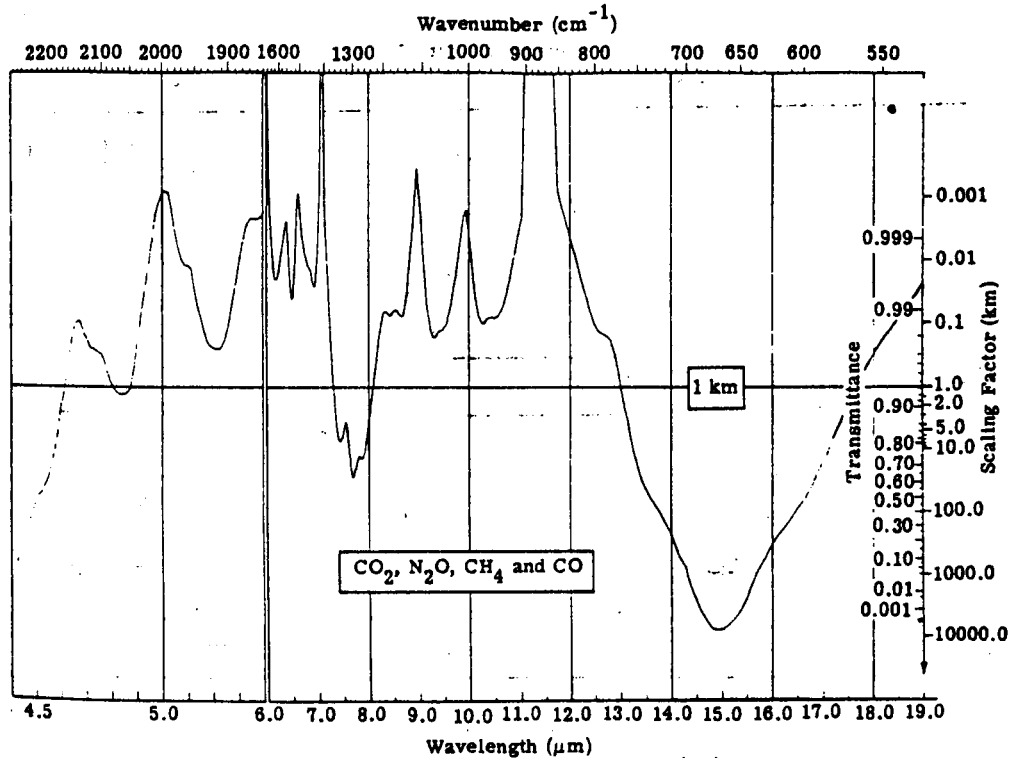
$\epsilon$  - pointwise emissivity

$e_{b, \lambda}$  - spectral emissive power

$\omega(x, y)$  - aperture solid angle

$*$  - convolution

# Emittance Calculation



(d) Transmittance of uniformly mixed gases (CO<sub>2</sub>, N<sub>2</sub>O, CO, CH<sub>4</sub>, O<sub>2</sub>) (4.5 to 19.0 μm).

## Transmittance-Beer's Law

$$\tau_{\lambda}(z) = \exp(-a_{\lambda}z)$$

Absorptance -emittance

$$\epsilon_{\lambda} = \alpha_{\lambda} = (1 - \tau_{\lambda})$$

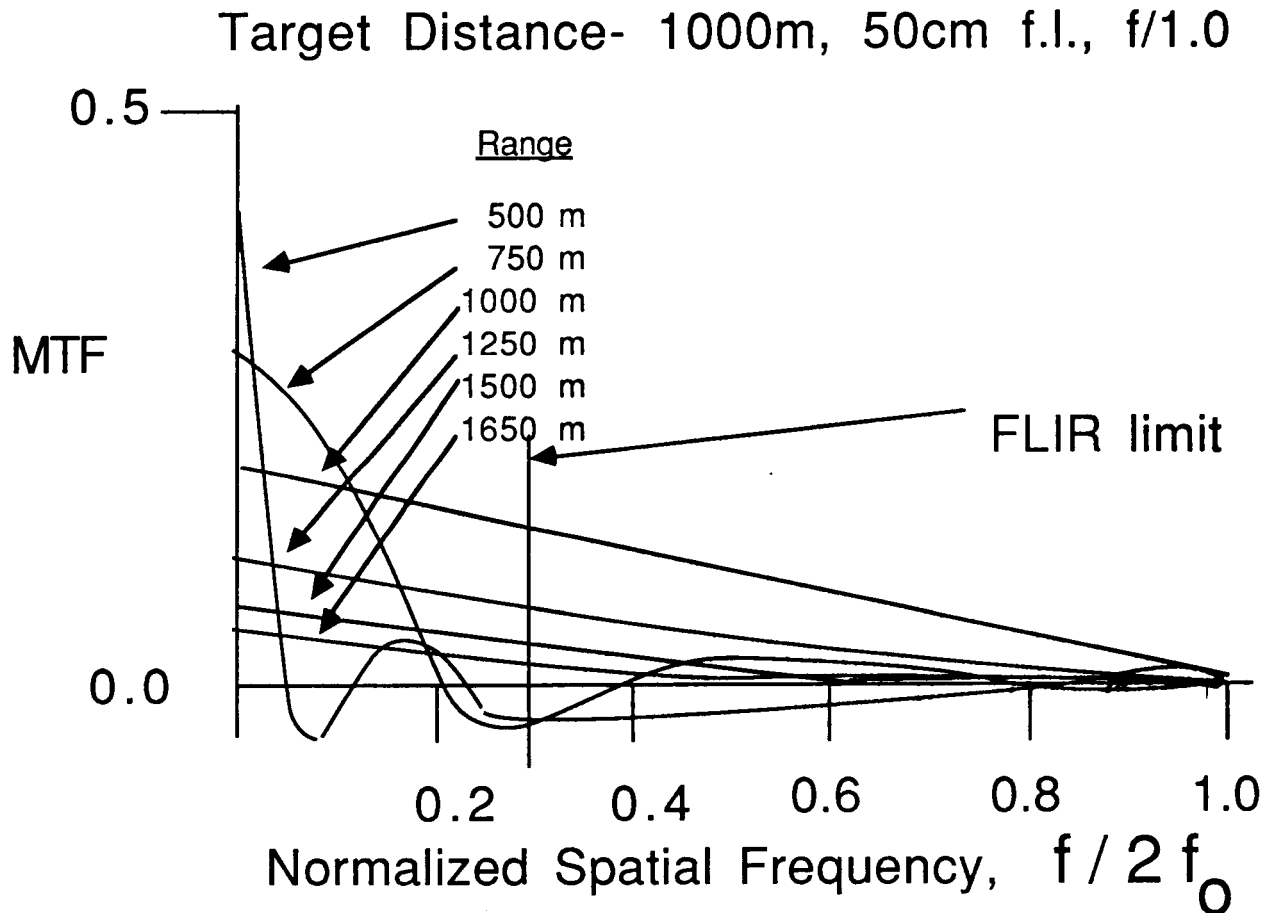
Local Emissivity

$$\epsilon = 1 - \exp(-a \delta z)$$

$$\delta z^3 = \text{volume of resolution cell}$$

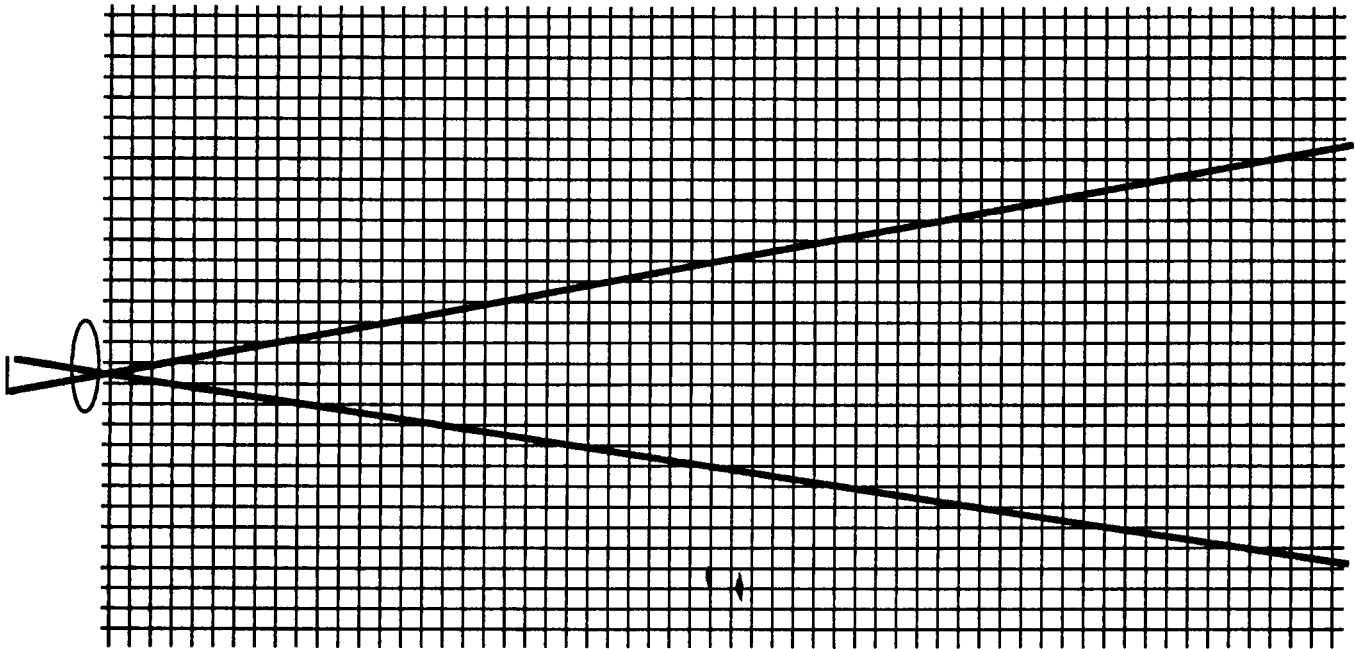
## Image Localization by Defocussing

Incoherent Imaging MTF, with atmospheric absorption



- At higher spatial frequencies, focal region contains most signal energy
- By high-pass spatial filtering signal can isolate focal region
- Upper limit imposed by sensitivity, spatial resolution of FLIR

# Imaging Simulations



## Model Features

- 2-D Fractally Generated Temperature Field
- 2 x 1 kilometers deep (1024 x 512 nodes)
- Uniform Emissivity and Absorptivity
- Intensity variation due to temperature fluctuation only
- 50 cm f.l., f /1.0 lens
- $\lambda = 14 \mu\text{m}$
- Separate MTF calculated for each z location
- Convection by rigid motion of all or part of

### Preliminary Conclusions

- Convection does result in displacement of x-correlation peak
- Lens alone is not an adequate spatial filter to isolate target region, digital filtering is also necessary
- Image enhancement routines including trend removal and high pass spatial filtering needed to improve performance.
- Need Hg-Cd-Te FLIR detector to obtain adequate SNR



## Future Work

- Assess the effects of refractive turbulence
- Adapt TASS Model for Imaging Simulation
  - Develop Model of sub-grid temp. fluctuation
  - Use standardized radiation model (HITRAN) to Account for precip. broad spectra.
- Several Flight Paths
- Obtain experimental FLIR images to assess suitability for this application.
- Simulate laser speckle imaging

## **Session I. Airborne-Sensors**

Investigation of Airborne Lidar for Avoidance of Wind Shear Hazards  
Russell Targ, Lockheed  
Roland L. Bowles, NASA LaRC

**INVESTIGATION OF AIRBORNE LIDAR  
FOR AVOIDANCE OF WINDSHEAR HAZARDS**

**Russell Targ  
Lockheed Missiles & Space Company, Inc.  
Research & Development Division  
Palo Alto, California 94304**

**and**

**Roland L. Bowles  
NASA Langley Research Center  
Hampton, Virginia 23665-5225**

**Presented at the  
Second Combined Manufacturers' and Technology  
Airborne Windshear Review Meeting**

**Williamsburg, Virginia**

**October 18-20, 1988**

INVESTIGATION OF AIRBORNE LIDAR  
FOR AVOIDANCE OF WINDSHEAR HAZARDS

p2y

Russell Targ  
Lockheed Missiles & Space Company, Inc.  
Research & Development Division  
Palo Alto, California 94304

and

Roland L. Bowles  
NASA Langley Research Center  
Hampton, Virginia 23665-5225

Abstract

A generalized windshear hazard index is defined, which is derived from considerations of wind conditions at the present position of an aircraft and from remotely sensed information along the extended flight path. Candidate airborne sensor technologies based on microwave Doppler radar, Doppler lidar, and infrared radiometric techniques are discussed in the context of overall system functional requirements. Initial results of a performance and technology assessment study for competing lidars are presented. Based on a systems approach to the windshear threat, lidar appears to be a viable technology for windshear detection and avoidance, even in conditions of moderately heavy precipitation. The proposed airborne CO<sub>2</sub> and Ho:YAG lidar windshear-detection systems analyzed in this paper can give the pilot information about the line-of-sight component of windshear threat from his present position to a region extending 1 to 3 km in front of the aircraft. This constitutes a warning time of 15 to 45 seconds. The technology necessary to design, build, and test such a brassboard 10.6- $\mu$ m CO<sub>2</sub> lidar is now available. However, for 2- $\mu$ m systems, additional analytical and laboratory investigations are needed to arrive at optimum 2- $\mu$ m rare-earth-based laser crystals.

Nomenclature

B	=	system bandwidth
d	=	telescope diameter
D	=	aircraft drag force
E	=	total aircraft energy (or laser pulse energy)
F	=	aircraft specific hazard index (nondimensional)
g	=	acceleration of gravity
$h_p$	=	aircraft potential altitude (energy height)
h	=	aircraft altitude
K(R)	=	round-trip extinction for range R
L	=	distance between adjacent range gates
R	=	range of return
T	=	aircraft thrust force
V	=	aircraft airspeed
W	=	aircraft weight
$W_h$	=	vertical component of inertial wind
$W_x$	=	horizontal component of inertial wind
$\beta$	=	backscatter cross section

$\gamma$	=	flight path angle relative to air mass
$\lambda$	=	laser wavelength
$\eta$	=	detection and mixing efficiency
$\tau$	=	forward-look alert time
$\nabla$	=	gradient operator

1. Background and Introduction

Low-altitude windshear is recognized by the commercial aviation industry as a major hazard. In the United States, during the period 1964 to 1985, windshear has been a contributing factor in at least 26 civil transport accidents and 3 incidents involving 500 fatalities and over 200 injuries. Numerous methods of reducing the low-altitude windshear hazard have been proposed by the airlines, airframe manufacturers, and the Government. The Federal Aviation Administration (FAA), as lead agency for civil aviation safety, has established an integrated windshear program plan which addresses the windshear problem through focused research and development efforts over a 5-year period. The National Aeronautics and Space Administration (NASA) has responded by signing a memorandum of agreement with the FAA (July 1986) to pursue a cooperative research program which addresses technical factors related to airborne detection, avoidance, and survivability of severe windshear atmospheric conditions. Key elements of the NASA research effort include characterization of windshear phenomena in the aviation context, airborne remote-sensor technology that provides forward-looking avoidance capability, and flight-management system concepts that promote risk-reduction piloting through timely and accurate transfer of information to flight crews. The NASA research thrust is directed at developing system concepts which embrace forward-looking sensor technology, thereby providing the flight crew with awareness of the presence of windshear with enough time to avoid the affected area and escape from the encounter.

This paper emphasizes the analysis of competing lidars for use in an airborne forward-looking system, to enable aircraft to avoid the hazards of low-altitude windshear. The analysis includes a definition of lidar sensor requirements, the formulation of a system to meet these requirements, and an investigation and simulation of the capabilities and limitations of such a system, together with recommendations identifying the most feasible and cost-effective laser for use in a lidar system for windshear detection and avoidance.

This paper is declared a work of the U. S. Government and is not subject to copyright protection in the United States.

The two lidar systems investigated, solid-state Ho:YAG at  $2.1 \mu\text{m}$  and  $\text{CO}_2$  at  $10.6 \mu\text{m}$ , appear able to meet the windshear warning requirements as determined by computer simulations of the 1985 Dallas/Fort Worth microburst event. The performance of Ho:YAG is potentially superior to that of the  $\text{CO}_2$  lidar, but Ho:YAG is far from being available at this time. On the other hand, the  $\text{CO}_2$  technology is quite mature, and has been tested extensively in both airborne and ground-based wind-field mapping applications.

## 2. The Threat From Windshear

National attention has focused on the critical problem of detecting and avoiding windshear since the crash on August 2, 1985, of Delta Air Lines Flight 191, a Lockheed L-1011, at the Dallas/Fort Worth International Airport. Other crashes and near misses caused by windshear have occurred almost annually.

The hazard of windshear arises principally from its deceptive nature: In a windshear situation, from a microburst or any other source, the pilot is confronted with a performance-increasing headwind, followed a few seconds later by a powerful, performance-decreasing tailwind. To cope with the headwind, the pilot may take actions to prevent the plane from climbing. These actions are then compounded by the lack of lift caused by the tailwind and downdraft, so that it may be impossible to keep the plane in the air. The downburst shown in Fig. 1 can be entirely invisible to the pilot and the ground controllers, and it need not be associated with any rain on the ground. In a NASA/FAA study of 186 windshear occurrences in 1983, the average change in wind speed was approximately 40 knots.<sup>1</sup>

The NASA/FAA Joint Airport Weather Study (JAWS)<sup>1</sup> observed and measured windshears at the Denver/Stapleton Airport over a 3-month period. The principal finding confirmed that "... low-altitude wind variability (or windshear) presents an infrequent but highly significant hazard to aircraft landing or taking off." From analysis of aircraft accidents where low-altitude windshear was a factor, it appears that the greatest hazards are caused by downdrafts and outflows produced by convective storms.

Pilots now receive inconsistent windshear warnings that are of questionable reliability. The ground-based data from anemometers must first be interpreted by trained meteorologists. The tower attempted to warn Flight 191 of windshear a full 2 min after it crashed. The *Windshear Training Aid*<sup>2</sup> produced by the NASA/FAA Integrated Program in 1986 carries the warning, "Maximum windshear capability of jet transports at heavy weight, for a windshear encounter at a critical location, is 40 to 50 knots wind-speed change. Some windshears cannot be escaped successfully [once they are actually entered]!". For this reason it is essential to emphasize avoidance rather than recovery. An onboard forward-looking windshear-avoidance system can warn the pilot, at the location marked "windshear entry" in Fig. 1, that he is approaching a wind hazard. When the plane is at the location "recover or crash," it can be too late to inform the pilot that he is in windshear.

## 3. Requirements for an Airborne Windshear Detection System

The fundamental requirement for a forward-looking, airborne windshear detection system is realtime remote sensing. This implies the ability to reliably measure line-of-sight and vertical components of wind velocity and to alert the crew when they are approaching a windshear hazard. The system should monitor the approach path, the runway, and the takeoff path, in both rain and clear-air conditions. This alert should be provided with enough warning time to allow the pilot to increase the energy of the plane and safely transit or avoid the microburst. The quantitative technical requirements are given in Table 1.

Table 1. Quantitative Technical Requirements

Minimum sensing range	1 to 3 km
Advance warning time	15 to 40 s
Range resolution	0.3 km
Velocity resolution	Approximately 1 m/s

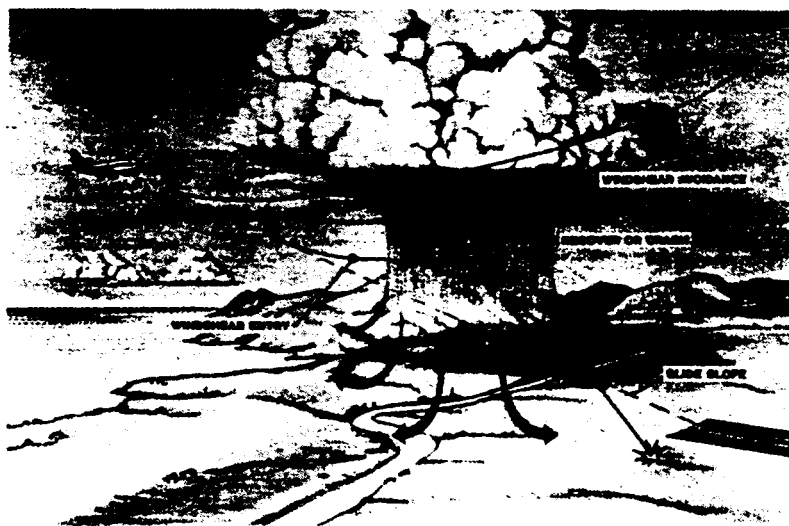


Fig. 1. The windshear problem.

There are additional functional requirements for any airborne system: It must not interfere with other instruments on the aircraft; it should be as small as possible; it should operate reliably in an aircraft environment for 2000 hours with little or no maintenance; and it should not require any expendable supplies that would have to be replenished. All these factors should work together to make a system that is almost free from false or nuisance alarms. The first specific hazard that should trigger a windshear alarm is a performance-decreasing wind (tailwind) which increases its velocity at a rate of 2 knots/s in the direction of travel of the aircraft. A second threatening condition is the downburst, which is considered a hazard when the vertical velocity reaches 1500 ft/min. A numerical hazard index "F" has been derived by NASA using both these factors, where  $F > 0.1$  is considered a potential aircraft hazard.

#### 4. Definition of Hazard Index

The key to the development of airborne windshear detection, warning, and avoidance systems is the identification of a hazard index. This index should exhibit a functional dependence on atmospheric states that can be reliably sensed, and scale with available aircraft performance in such a way that the index predicts impending flight-path deterioration. The hazard index must also account for factors such as the statistical nature of the windshear threat, fusion of present position and "forward-looking" sensor capabilities, and the development of objective methods for determining system warning thresholds which consider the potential for nuisance alerts. A hazard index which has the above properties and is based on accepted fundamentals of flight mechanics and current state of knowledge of windshear phenomena has been derived.

An analysis was conducted which revealed the importance of aircraft energy balance for flight in spatially and temporally varying windfields. This energy-state analysis showed that aircraft motions should be referenced to the accelerated and nonhomogenous airmass which typifies windshear phenomena. The concepts of airplane total energy and rate of change of total energy are useful in interpreting the impact of windshear on aircraft performance. The airplane total energy is defined as the sum of the air-mass relative kinetic energy and the inertial potential energy. Air-mass kinetic energy is used since only airspeed, not ground speed, describes the airplane's ability to climb or maintain altitude. Inertial potential energy is likewise used since it is altitude above the ground that is useful to the airplane.

Therefore, airplane total specific energy (energy per unit weight), or *potential* altitude, is defined as:

$$h_p = \frac{E}{W} = \frac{V^2}{2g} + h \quad (1)$$

where  $V$  is airspeed,  $W$  is aircraft weight, and  $h$  is aircraft altitude. The rate of change of specific energy—also defined as the potential rate of climb of the airplane, assuming negligible energy loss when trading airspeed for climb rate—is given by:

$$\dot{h}_p = \frac{\dot{E}}{W} = \frac{V}{g} \dot{V} + \dot{h} \quad (2)$$

When combined with appropriate aircraft equations of motion,<sup>3</sup> the potential rate of climb given by Eq. (2) reduces to:

#### WINDSHEAR "HIT"

$$\dot{h}_p = \frac{\dot{E}}{W} = \left\{ \frac{T-D}{W} - \left[ \frac{\dot{W}_x}{g} \cos \gamma + \frac{\dot{W}_h}{g} \sin \gamma - \frac{W_h}{V} \right] \right\} V \quad (3)$$

where  $(T-D)/W$  is the ratio of aircraft thrust minus drag to weight,  $W_x$  and  $W_h$  are the horizontal and vertical wind velocity components, respectively, and  $\gamma$  is the flight-path angle relative to airmass.

The dot notation in Eq. (3) indicates the substantial derivative with respect to time, since the wind velocity components depend explicitly on aircraft position.

For representative numerical values of windshear gradients, and for flight-path angles compatible with stabilized flight, i.e., for  $\gamma \approx 0$ , the hazard index labeled as windshear "hit" in Eq. (3) is accurately approximated as

$$F = \frac{\dot{W}_x}{g} - \frac{W_h}{V} \quad (4)$$

and Eq. (3) takes the approximate form:

$$\dot{h}_p = \frac{\dot{E}}{W} = \left[ \frac{T-D}{W} - F \right] V \quad (5)$$

Equations (4) and (5) explicitly define the quantitative impact of windshear on aircraft energy state and the rate-of-climb capability. The analysis reveals that the rate of change of specific energy (potential climb rate) depends linearly on a nondimensional parameter  $F$ , which contains only information regarding air mass movement. Further analysis indicates that the subject parameter can be physically interpreted as the loss or gain in available excess thrust-to-weight ratio due to downdrafts, updrafts, and horizontal windshear, thus providing an aircraft-specific index on which to base annunciated warnings.

The derived hazard index given by Eq. (4), referred to as the  $F$ -factor, exhibits the following properties:

1. It scales with available aircraft performance in such a way as to predict impending flight-path deterioration.
2. It shows a functional dependence on atmospheric states that can be reliably sensed.
3. It is applicable to both in-situ and remotely sensed windshear information.
4. It is compatible with stringent nuisance-alarm requirements.

Positive values of  $F$  indicate a performance-decreasing situation for the aircraft, whereas negative values indicate a performance-increasing condition due to atmospheric disturbance. Considering jet transports in take-off configuration and the current state of knowledge regarding windshear phenomena, typical numerical

values for the terms under hazardous conditions making up the F-factor are:

$$0.1 \leq \frac{T-D}{W} \leq 0.3; |\dot{W}_x| \leq 0.3 g; \left| \frac{W_h}{V} \right| \leq 0.25.$$

Note that a headwind loss of  $\dot{W}_x = 0.1 g$  (2 knots/s) has the same impact on aircraft performance (F value) as a downdraft  $W_h = -15$  knots (-1500 ft/min), considering a reference airspeed of 150 knots. Figure 2 shows the "safe operations" conditions as a function of the F-factor variables.

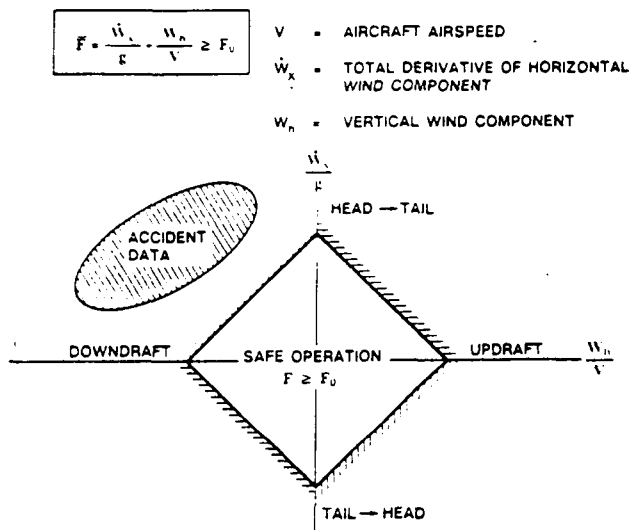


Fig. 2 Definition F-factor hazard index.

A possible airborne windshear detection, warning, and avoidance system architecture, which flows from the application of the F-factor concept, is shown in Fig. 3. The proposed architecture is compatible with a single-tier warning system (no amber caution) and provides for fusion of "present position" information,  $F(t)$ , with "forward look" information,  $F(t + \tau)$ . The prediction interval  $\tau$  is determined by a preselected and interrogated range gate divided by current aircraft ground speed. A preset hazard threshold  $F_0$  is incorporated, which, when exceeded below a specified aircraft altitude, provides an alert to the flight crew. Any combination of horizontal windshear and/or vertical wind that results in F less than the threshold value indicates safe aircraft

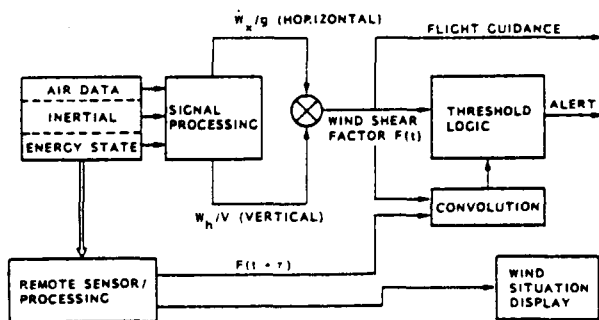


Fig. 3 Fusion of present-position and predictive information.

operation in relation to available excess thrust-to-weight ratio for that aircraft. A threshold exceedance that persists for a sufficient period of time warrants the annunciation of a windshear warning, which indicates to the crew that the affected area should be avoided or an escape maneuver should be initiated. The alert and warning threshold is determined by considering the maximum permissible F in relation to available aircraft performance capability while minimizing potential for nuisance warnings. Research indicates that threshold values for F between 0.1 and 0.15 are representative for landing and take-off phases of flight for jet transport aircraft, considering factors such as aircraft type, configuration, and range of gross weights. Figure 4 illustrates average values for windshear F-factors derived from five aircraft accidents. The data presented indicate that, in all cases, the average F-factor exceeded the ability of the airplane at maximum weight to accelerate in level flight.

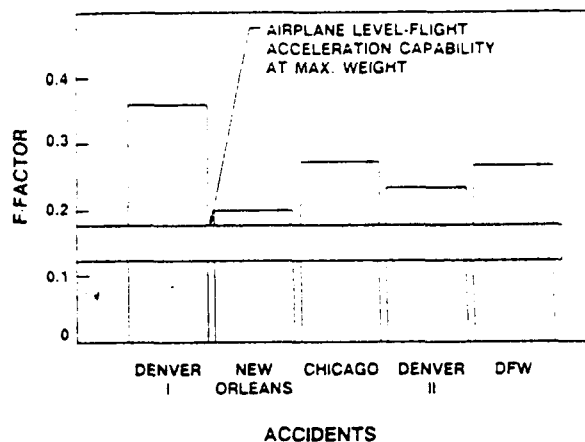


Fig. 4 Accident windshear F-factors compared to airplane capabilities.

The F-factor concept can be extended to forward-looking sensors through utilization of spatial wind measurements along a given line-of-sight direction, a characteristic which is typical for pulsed-Doppler detection and ranging systems. The substantial derivation expressed in Eq. (4), assuming a "frozen wind field" hypothesis, can be approximated as:

$$\dot{W}_x = \nabla W_x \cdot V_i + \frac{\partial W_x}{\partial t} = \frac{\partial W_x}{\partial X} V \quad (6)$$

where  $V_i$  is the inertial velocity vector of the aircraft. If Eq. (6) is substituted into Eq. (4) and the result linearized about the  $i$ th. range gate along a ray of the forward-looking sensor, one obtains the recursion

$$F(i+1) = F(i) + \frac{V}{gL} [W_x(i+2) - 2W_x(i+1) + W_x(i)] - \frac{W_h(i+1)}{V} \quad (7)$$

The quantity  $L$  is defined as the distance between any two adjacent range gates along a line-of-sight ray of the

active sensor. Typical values for  $L$  are between 150 m and 500 m, depending on sensor pulse width. The realtime calculation of Eq. (7) predicts the distribution of hazard index based on absolute wind measurements at predetermined range gates. Note that  $F(0)$ ,  $W_x(0)$ , and  $W_y(0)$ , which can be determined from present position *in situ* measurements, are required to initialize the iteration. Application of the algorithm described above, in a variety of simulation studies, has demonstrated the need for presmoothing the spatial wind measurements in order to suppress small-eddy turbulence, otherwise an unacceptable incidence of nuisance warnings may occur.

## 5. Approaches to Airborne Windshear Detection

### 5.1 Lidar Systems

For more than two decades, optical heterodyne detection has been successfully used to measure the frequency of Doppler-shifted laser light scattered from moving aerosols. This technique has been pioneered by many researchers, including those working with both NASA and NOAA. Although wind-velocity measurements are routinely made with good accuracy to ranges of more than 10 km in clear air, the range is seriously degraded by rain. The attenuation from radiation in the infrared is approximately 9 dB/km per inch of rain per hour.<sup>4</sup> Thus, a moderate-size airborne lidar system, which may have 3- to 5-km range in clear air, will have its range reduced to 1 km in a rain of 3 in./h, such as one might find in the core of a wet microburst. However, even under these severe conditions, 14 s of advance warning can be provided.

Although the subject of this paper is the analysis of lidar approaches to windshear detection, it is useful to put lidar into context with two other candidate systems which are presently under active development to meet this goal.

### 5.2 Microwave Systems

High-power ground-based Doppler radars operating at C-band and X-band are able to measure wind velocity at ranges of 10 to 20 km by measuring the scattered radiation primarily from precipitation, ice crystals, or other debris in the air. Microwave systems receive only minimal returns from dry air. Although windshear is usually associated with violent thunderstorms in the southern United States, 80 percent of the observed windshear events in the Denver study (JAWS) were dry at ground level. If the wind data for the flight paths could be rapidly updated and made available to the pilots, flight safety could be greatly improved. A major problem with on-airport radars—and to an even greater extent airborne radars—is the appearance of ground clutter. For the airborne system, the clutter return from the moving terrain along the flight path has a much greater amplitude (approximately +60 dB) than, and a frequency in the same band as, the hoped-for Doppler return from the wind. In comparing airborne radars with the ground-based systems such as those participating in the successful JAWS measurements, one must take into account the reduction in transmitter power that such an airborne system will have available, as well as the reduced antenna aperture, leading to a beam divergence of several degrees. All these factors have a significant impact on the ultimate achievable signal-to-noise ratio (SNR) (-30 to -40 dB as compared with a ground-based

system). Details regarding the NASA airborne windshear radar research efforts are found in Ref. 5.

### 5.3 Radiometer

Measurements indicate that there is a temperature gradient associated with the formation of a windshear. It appears that this gradient can be measured by an airborne infrared radiometer. The radiometers which have been used for this purpose measure emission from the 14- $\mu$ m band of atmospheric CO<sub>2</sub>. The technique compares emission from CO<sub>2</sub> in the immediate neighborhood of the aircraft to the emissions from the CO<sub>2</sub> in the air 2 or 3 km away. It is conjectured that the more negative this temperature gradient, the steeper the gust front causing it. Although it appears that radiometers of this type can detect temperature gradients associated with microbursts under favorable conditions, the question of nuisance alarms has not been addressed, since it has not yet been determined what other types of atmospheric phenomena cause similar gradients. Industry initiatives to exploit infrared technology for airborne windshear detection are discussed in Ref. 6.

## 6. Successful Lidar Wind-Velocity Measurements

Since early work in the 1970's, there have been many advances in airborne laser velocimetry. James Bilbro, at NASA's Marshall Space Flight Center, has successfully measured wind velocity from an aircraft using a modulated CO<sub>2</sub> continuous wave (cw) laser followed by a large high-power amplifier that produced 10 mJ at 10.6  $\mu$ m.<sup>7</sup> Bilbro's Doppler lidar operates in clear air and has a range of more than 5 km. A compact and reliable laser system has been flight-tested for several years by J. Michael Vaughan of the Royal Signals and Radar Establishment.<sup>8</sup> His lidar used a cw CO<sub>2</sub> laser focused 300 m in front of the airplane to measure backscatter coefficients at many European and American test sites and airports. Vaughan also uses optical heterodyne detection to determine the plane's velocity from the Doppler shift in the radiation scattered from the aerosols illuminated by the laser. Because it is a cw focused system, rather than pulsed, it is difficult to extract range information, and its look-ahead is limited to a warning of only a few seconds. In recent years, pulsed transversely excited atmospheric pressure (TEA) CO<sub>2</sub> lasers have been made increasingly reliable for long-term operation. Such a system has been used with good success by R. Michael Hardesty at NOAA to measure wind velocity and map wind fields over a 20-km range with a lidar system located in a van.<sup>9</sup> From these studies it is clear that similar systems using smaller lasers can be developed for airborne applications.

## 7. Simulation and Performance Analysis of the Ho:YAG and CO<sub>2</sub> Lidars

The approach simulated in our study is that of a pulsed laser which is focused 3 km in front of the aircraft and is then coherently detected to yield the Doppler shift in the light scattered back to the aircraft. A typical optical heterodyne transceiver is shown in Fig. 5. More than 100 lidar simulation runs have been made for NASA by Coherent Technologies, Inc., computing end-to-end signal-to-noise ratios and velocity errors for two candidate lidars as a function of distance from the core of the Dallas/Fort Worth microburst. A simplified form of the



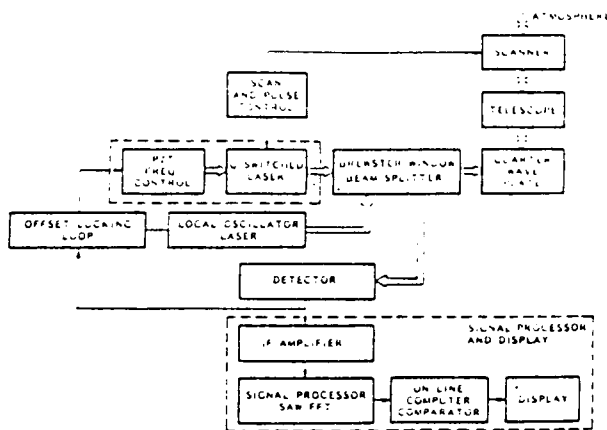


Fig. 5 Typical optical heterodyne transceiver.

lidar equation used for these calculations is shown below:

$$\frac{S}{N} = \frac{\pi E D^2 \beta \lambda \eta K(R)}{8 R^2 B h}$$

where

- $E$  = laser pulse energy
- $D$  = telescope diameter
- $\beta$  = backscatter cross section
- $\lambda$  = laser wavelength
- $\eta$  = detection and mixing efficiency
- $K(R)$  = round-trip extinction for range  $R$
- $R$  = range of return
- $B$  = system bandwidth
- $h$  = Planck's constant

Representative results from these analyses are presented by Huffaker.<sup>10</sup> A conclusion of this work is that, in order to demonstrate a windshear threat, it is sufficient for a sensor system to determine that there is a performance-increasing wind followed spatially by a performance-decreasing wind, where these changes are of the order of 10 to 20 knots per half kilometer. An initial assumption has been that 30 s of warning time was a requirement of an airborne windshear-detection system. Using the Ho:YAG or CO<sub>2</sub> lidars examined in this study, this warning time is achievable in most, but not all, microburst situations. In the Dallas/Fort Worth microburst, the peak rain rate was 3.85 in./h at the core. The starting parameters for the two lidars are shown in Table 2.

Table 2. Base-Case Lidar Parameters

Parameters	Lidar System	
	Ho:YAG(2.1 $\mu$ m)	CO <sub>2</sub> (10.6 $\mu$ m)
500-m Backscatter Coeff. (1/(m·sr))	$1.28 \times 10^{-6}$	$5 \times 10^{-8}$
Efficiency ( $\eta_T = \eta_o \eta_c \eta_q$ )	0.1	0.1
Attenuation (dB/km)	0.1	1.0
Pulse Energy (mJ)	5	5
Bandwidth (MHz)	10	1.0
Pulse Length ( $\mu$ s)	0.5	1.0
Mirror Diameter (cm)	15	15

Using the lidar equation to calculate SNRs, we find that a 5-mJ CO<sub>2</sub> lidar on board an aircraft 4 km from the core center will be able to penetrate approximately 250 m into the core. This lidar will completely sense the performance-increasing portion of the winds, but only the start of the performance-decreasing winds in the 1985 Dallas Fort Worth example.

If an aircraft is 2 km from the microburst core center, the CO<sub>2</sub> lidar can penetrate approximately 700 m into the core of the microburst. This increase in penetration allows the lidar to show clearly a significant portion of the performance-decreasing winds. Reducing the look-ahead distance from 4 km to 2 km reduces the warning time to ~12 s before the aircraft reaches the near "edge" of the microburst. We have examined what energy-increasing strategies a pilot can employ, for example, in a Boeing 727 with 12 s in which to prepare for an encounter with a microburst. If the pilot has confidence in the warning he receives from the lidar-based windshear alarm, he can initiate a "go-around" procedure with the aircraft throttle setting advanced to full thrust and a pitch attitude of 15° at a rate of 4°/s. It is then possible for him to gain 500 ft of altitude within the available 12 s. If the go-around was initiated at an altitude of 400 ft the microburst transit would be accomplished safely. With a warning representative of that which might be obtained with an *in situ* reactive system, the aircraft would not achieve any altitude margin prior to windshear encounter. All of these data were obtained from a simulation carried out on a 727-2A flight simulator, for a plane with gear down and 30° flaps.

Figure 6 shows the signal-to-noise ratio (SNR) as a function of range from the Dallas/Fort Worth microburst for a 5-mJ CO<sub>2</sub> lidar for two aircraft locations. It also shows the radial wind velocity profile associated with this microburst. The Ho:YAG system has a reduced atmospheric attenuation of approximately 0.1 dB/km as compared with 1.0 dB/km for CO<sub>2</sub>, as a result of this initially greater SNR, and it has somewhat superior penetration into the rain-filled core of the microburst as compared with CO<sub>2</sub>. This performance is shown in

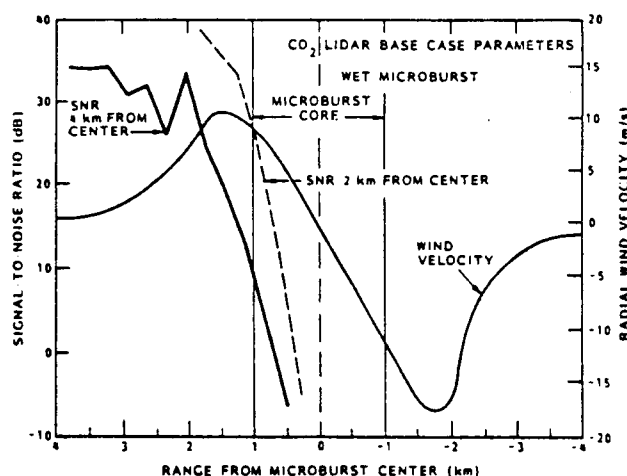


Fig. 6 CO<sub>2</sub> lidar signal-to-noise ratio and true wind velocity versus distance from the microburst core for two aircraft positions, 2 and 4 km from the microburst center.

Fig. 7. The effect of differing SNRs of the 10- $\mu$ m system is again apparent when we calculate velocity error as a function of range. This calculation is plotted in Fig. 8 for dry-air conditions. The velocity error  $\sigma(v)$  is based on Zrnic's analyses as recently described by Kane.<sup>11</sup>

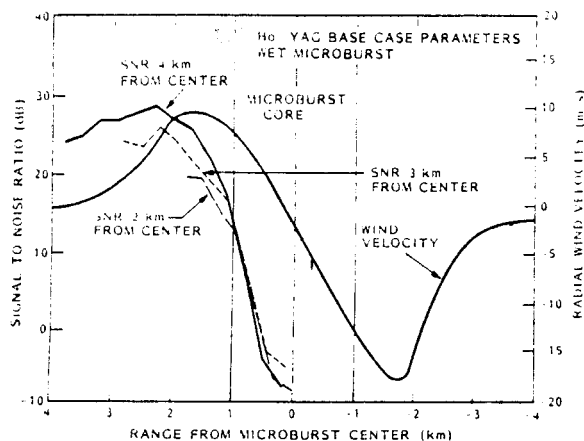


Fig. 7 Ho:YAG lidar signal-to-noise ratio and true wind velocity versus distance from the microburst core for three aircraft positions.

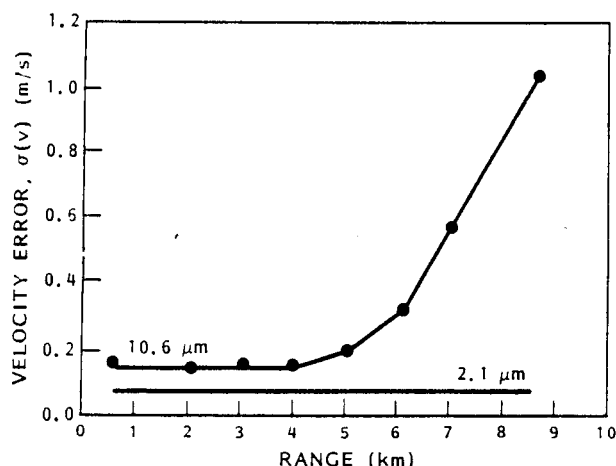


Fig. 8 Comparison of velocity errors for 2.1- $\mu$ m and 10.6- $\mu$ m lidars.

#### 8. Lidar Range in Rain and Minimum Required Advance Warning Time

It is well known that lidar has the potential for measuring wind velocity in clear air. One of the overriding concerns of the NASA program has been to determine the performance of lidar systems under conditions of precipitation, both light and heavy. We have made use of the measurements of attenuation in rain by Chu and Hogg<sup>4</sup> and the backscatter measurements of Rensch and Long<sup>11</sup> to calculate the range in rain for unity SNR of our base-case lidar as a function of rain rate. Unity SNR is chosen because the system still has a satisfactory velocity error for that SNR. The data in Fig. 9 show that

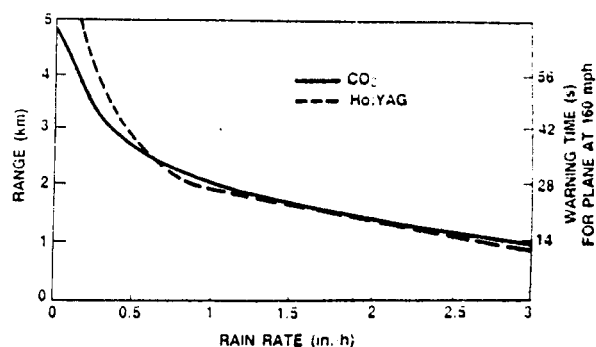


Fig. 9 Range in rain for unity SNR 5-mJ CO<sub>2</sub> and Ho:YAG lidars.

even in a homogeneous rain field of 3 in./h, the base-case lidars can measure wind velocity a kilometer in front of the aircraft. It should be noticed that for moderately heavy rain (2 in./h) both lidar systems have approximately the same penetration capability, 2 km. This is because the attenuation in rain is very large as compared with the differences in the two lidars. At a rain rate of 3 in./h, the round-trip attenuation is -48 dB/km.

The performance degradation of lidars in rain raises several important questions, key among them being, what range of forward-look alert times is required to assure aircraft survivability and flight-crew acceptance of the attendant windshear cockpit automation? A definitive answer to this question is not available at this time, because of the complex issues involving human factors and piloting technique, flight guidance and windshear information display, and considerations of aircraft performance capabilities. Figure 10 shows the change in aircraft energy height accrued from the time of annunci-ated warning to shear exit, as a function of forward-look

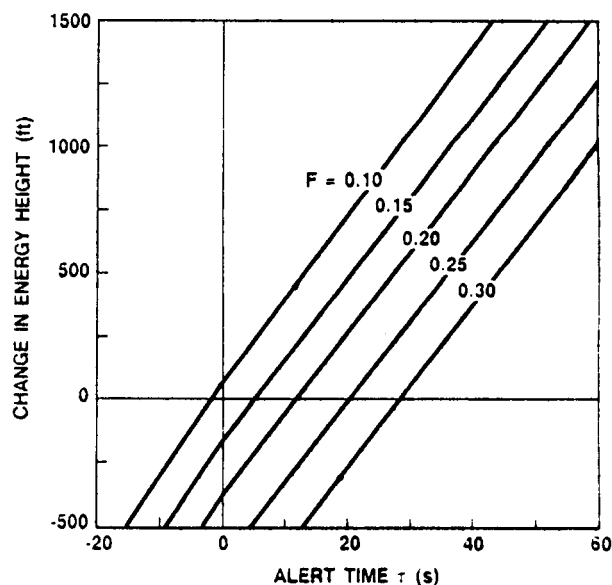


Fig. 10 Change in energy height as a function of forward-look alert time.

alert time, for several values of hazard index  $F$ . Negative values of  $\tau$  represent reactive windshear alerting systems (or no alert at all), whereas positive values of  $\tau$  represent advanced warning times achievable with remote sensing of atmospheric windshear conditions. Figure 10 clearly demonstrates the benefits and payoff attendant to forward-look windshear detection and warning system concepts. The aircraft selected for this analysis is typical of a modern, medium-range twin turbojet transport. Prior to windshear encounter, the aircraft was assumed to be in approach configuration with a microburst windshear located between the aircraft's current position and the runway threshold. Simplifying assumptions used in the calculations were constant  $F$ -factor once the shear is encountered, no change of aircraft configuration, and inclusion of representative latency for engine spool-up characteristics once the crew has elected to execute a windshear escape maneuver. Comparison of Figs. 9 and 10 suggests that lidar performance in moderate to heavy rain is adequate to significantly enhance aircraft survivability, although for short forward-look alert times, complete avoidance of microburst windshear may not be possible. Preliminary results of piloted simulation studies, jointly conducted by Boeing and NASA, tend to confirm the data presented in Fig. 10. Tentative results of the simulator study indicate that short alert times (15 to 30 s) can enable aircraft to attain safe altitude prior to shear entry, and are assessed as timely by the simulator test subjects.

Performance of the Ho:YAG and CO<sub>2</sub> lidar systems has also been evaluated for the "dry" microburst case, of the type typically encountered at Denver/Stapleton Airport. Such a case might include virga, but no rain reaching the ground. Figure 11 shows the SNR for the two lidars, as a function of aircraft distance from the core of the microburst. The true wind velocities are also shown. The velocity error for each system is less than 1 m/s for ranges out to 7 km in front of the aircraft.

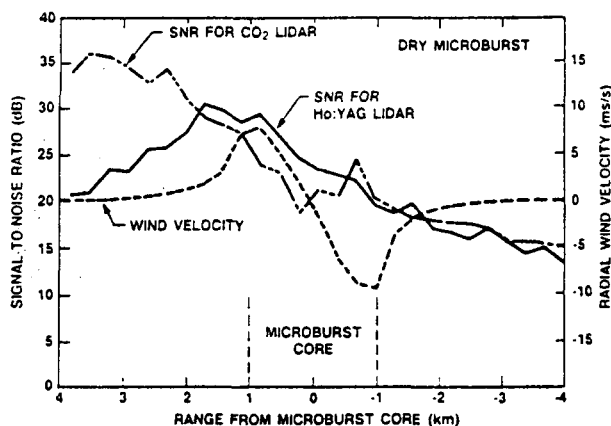


Fig. 11 Signal-to-noise ratio and true wind velocity versus distance from core of a dry microburst.

## 9. Lidar Hardware Evaluation

One of the goals of the program was to evaluate the state of the art with regard to laser performance and reliability. Together with our subcontractors, Spectra Technology of Seattle, Washington, and Lightwave Electronics of Mountain View, California, we have made

detailed performance estimates for CO<sub>2</sub> and Ho:YAG lasers. Both laser systems appear to have the capability to meet the program objectives, with the CO<sub>2</sub> laser having a significant advantage in technical maturity. A 5-mJ radiofrequency pumped waveguide CO<sub>2</sub> laser represents the state of the art for compact, reliable CO<sub>2</sub> lasers and, in the Q-switched mode of operation, appears to be a very low-risk solution to our system requirements. This type of compact, long-lived laser has already demonstrated adequate frequency stability in airborne applications. We have carried out a schematic optomechanical design of an airborne CO<sub>2</sub> lidar using this laser and other commercially available components. The resulting optical package, including laser transmitter, local oscillator, detector, and beam scanner, has a volume of approximately 3 ft<sup>3</sup>.

The theoretical performance of the 2- $\mu$ m lidar appears superior to that of the 10- $\mu$ m lidar; however, only very low laser output efficiency has been seen to date for room-temperature, Q-switched, 2- $\mu$ m lasers. There are also several remaining scientific and technological questions for the solid-state 2- $\mu$ m lidar: (1) Will single-mode oscillation be possible? (2) Will efficient Q-switching be possible? (3) Will practical detectors with adequate frequency response reach the market? (4) Will pump diodes meet their projected lifetime? Efforts were made to identify the potential 2- $\mu$ m system components together with their likelihood of success, using inputs from the several researchers. Unlike the CO<sub>2</sub> situation, there are no Ho:YAG vendors, only researchers. Therefore, if we had to select which laser system should be incorporated into the windshear lidar today, we would have no choice but to select the 10- $\mu$ m system. A conceptual design layout for the optical head of an airborne windshear is shown in Fig. 12.

## 10. Conclusions

Lidar appears to be a viable approach to windshear detection and avoidance, even in conditions of moderately heavy precipitation. The technology necessary to design, build, and test a brassboard 10- $\mu$ m CO<sub>2</sub> lidar is available. The airborne lidar windshear-detection systems analyzed in this program can give the pilot information about the line-of-sight component of windshear threat from his present position to a region extending 2 to 3 km in front of the aircraft. Techniques to measure and display vertical wind components and spatial distribution are a significant part of the windshear problem, and will be addressed in our continuing investigation. Although an eye-safe lidar at 2  $\mu$ m enjoys some performance advantages, the lasers and detectors for such a lidar have not yet been sufficiently developed to support their use in a near-term system. In the long term, diode-pumped solid-state lidars could well supplant CO<sub>2</sub>.

Although both CO<sub>2</sub> and Ho:YAG systems are shown feasible for airborne windshear detection in this study, several important questions remain to be answered before final decisions on development are made. Specifically, additional simulation studies are needed to investigate techniques to measure both the radial (line-of-sight) and vertical winds. A "dry" microburst case will be examined in the same way the present "wet" microburst was analyzed. Lidar scanning techniques will be investigated to allow modeling of the spatial extent of the threat, as well as radial and vertical components. The signal-processing algorithms to define

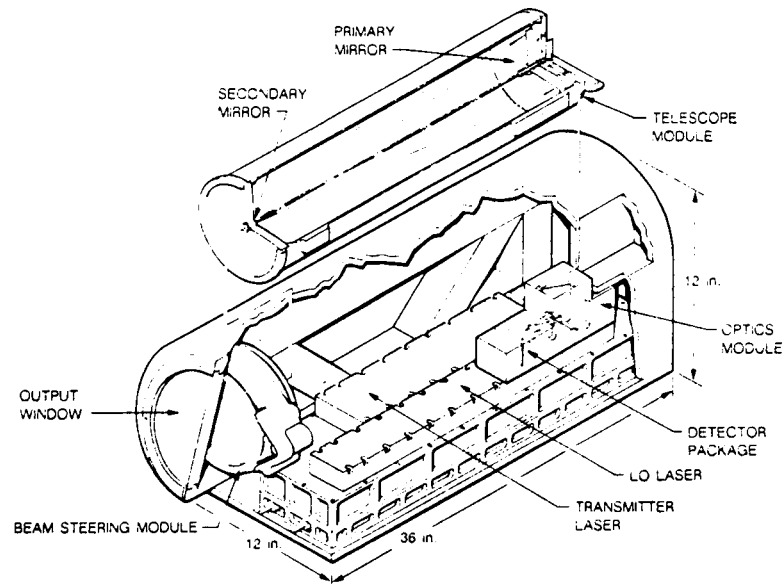


Fig. 12 Conceptual design of an airborne CO<sub>2</sub> laser radar.

the windshear threat must be examined along with recent advances in lidar signal processing. Developments in CO<sub>2</sub> and solid-state technology should continue to be monitored. A more fully developed windshear hazard analysis and warning criterion should be developed and incorporated into the computer simulation.

Finally, some of these questions can be answered definitively only through an airborne sensor-validation program. Such a program would be aimed at determining lidar performance against a windshear threat, characterizing that threat, examining lidar system performance in turbulent flows, and collecting valuable data on windshear phenomenology.

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## **Session I. Airborne-Sensors**

**2  $\mu$ m Lasers for Wind Shear Detection: A Technology Assessment**  
Mark Storm, Roland Bowles, and Bruce Conway, NASA LaRC

**2  $\mu$ m LASERS FOR WIND SHEAR DETECTION:**  
**A TECHNOLOGY ASSESSMENT**

**MARK STORM**  
**NASA/STX**

**ROLAND BOWLES**  
**N A S A**

**BRUCE CONWAY**  
**NASA**

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## OUTLINE

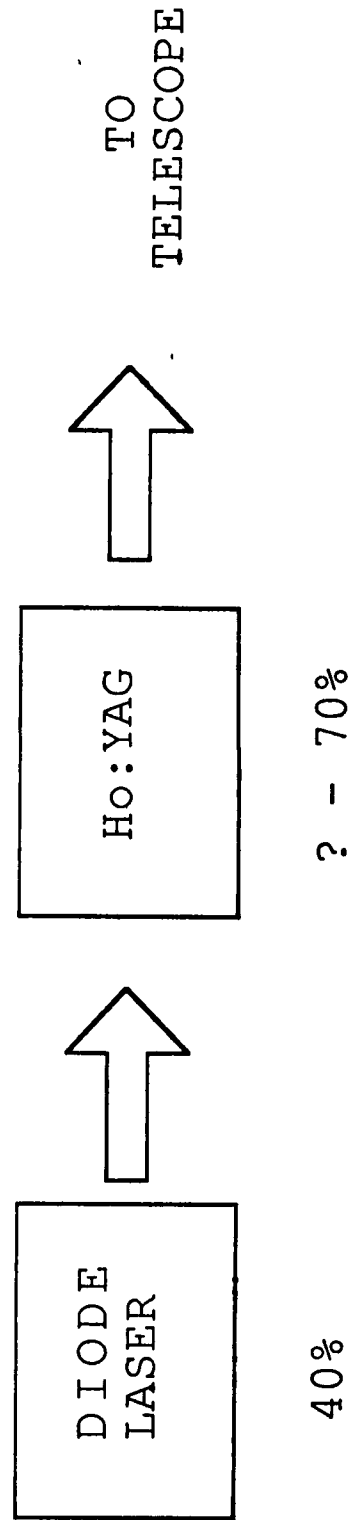
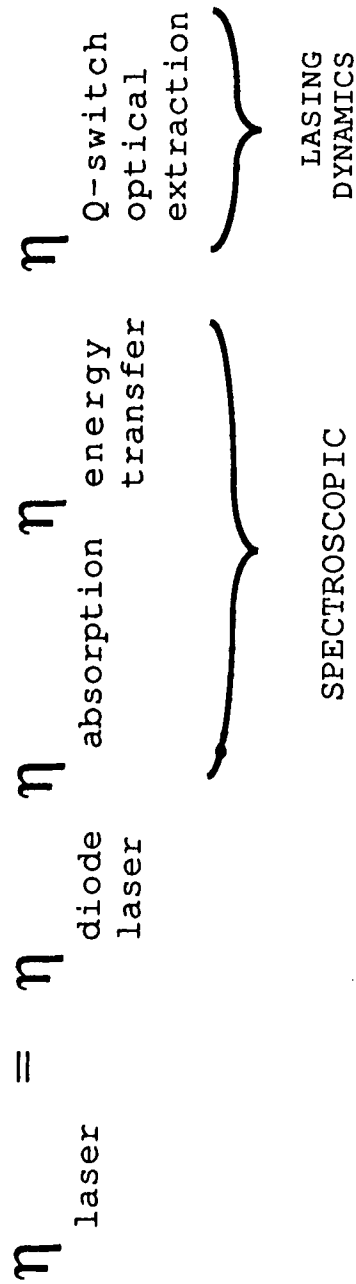
- PURPOSE/GOAL OF THIS TASK
- LASER REQUIREMENTS
- LASER BLOCK DIAGRAM
- LASER EFFICIENCY CONSIDERATIONS
- LASER CRYSTAL PARAMETERS  
SPECTROSCOPY/LASER DATA
- STATE OF THE ART

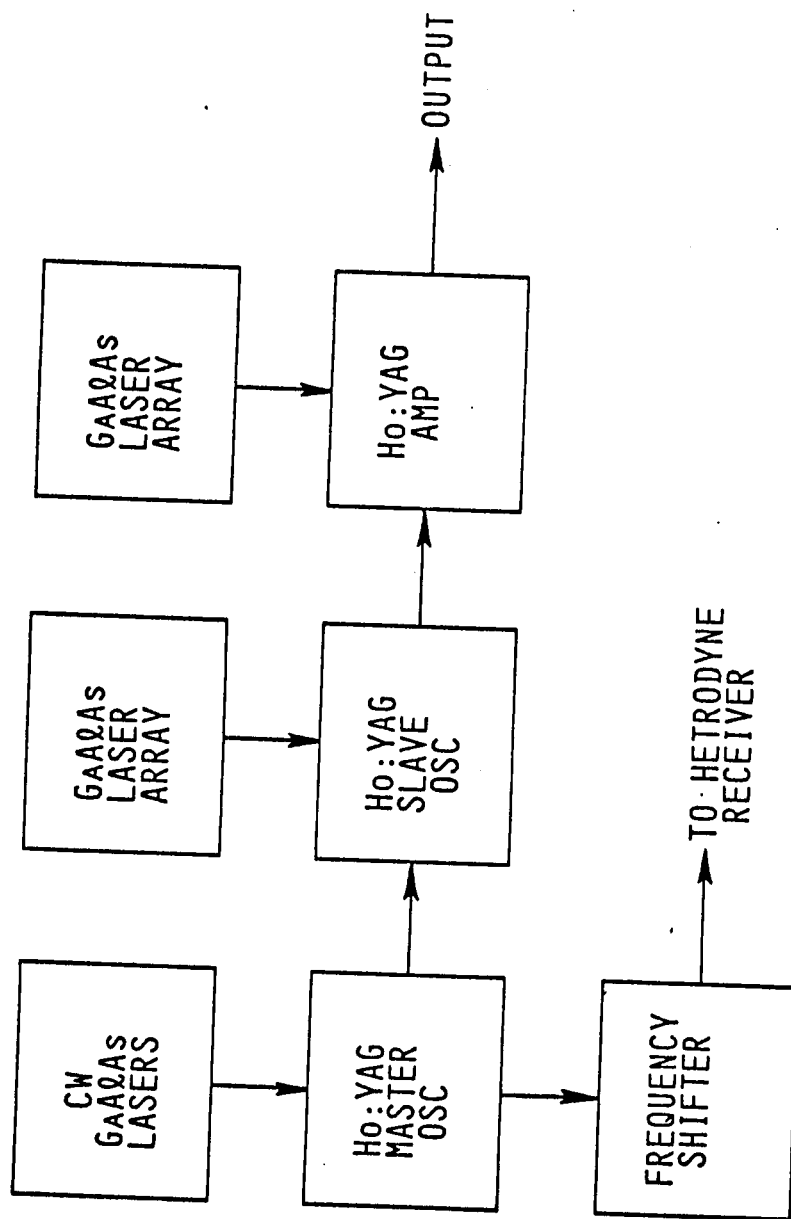
## LASER REQUIREMENTS:

- PULSED, Q-SWITCHED, SINGLE-MODE
- LASER ENERGY: 5 mJ
- REPETITION RATE: 150-200 Hz
- BANDWIDTH: 10 MHz
- COMPACT, EFFICIENT, RELIABLE



## 2 MICRON LASER EFFICIENCY





CLEAR AIR TURBULENCE TRANSMITTER

#

1.00E 01

Ho:Tm:YAG Fluorescence  
785 nm excitation  
NASA

Intensity

0.00E 00

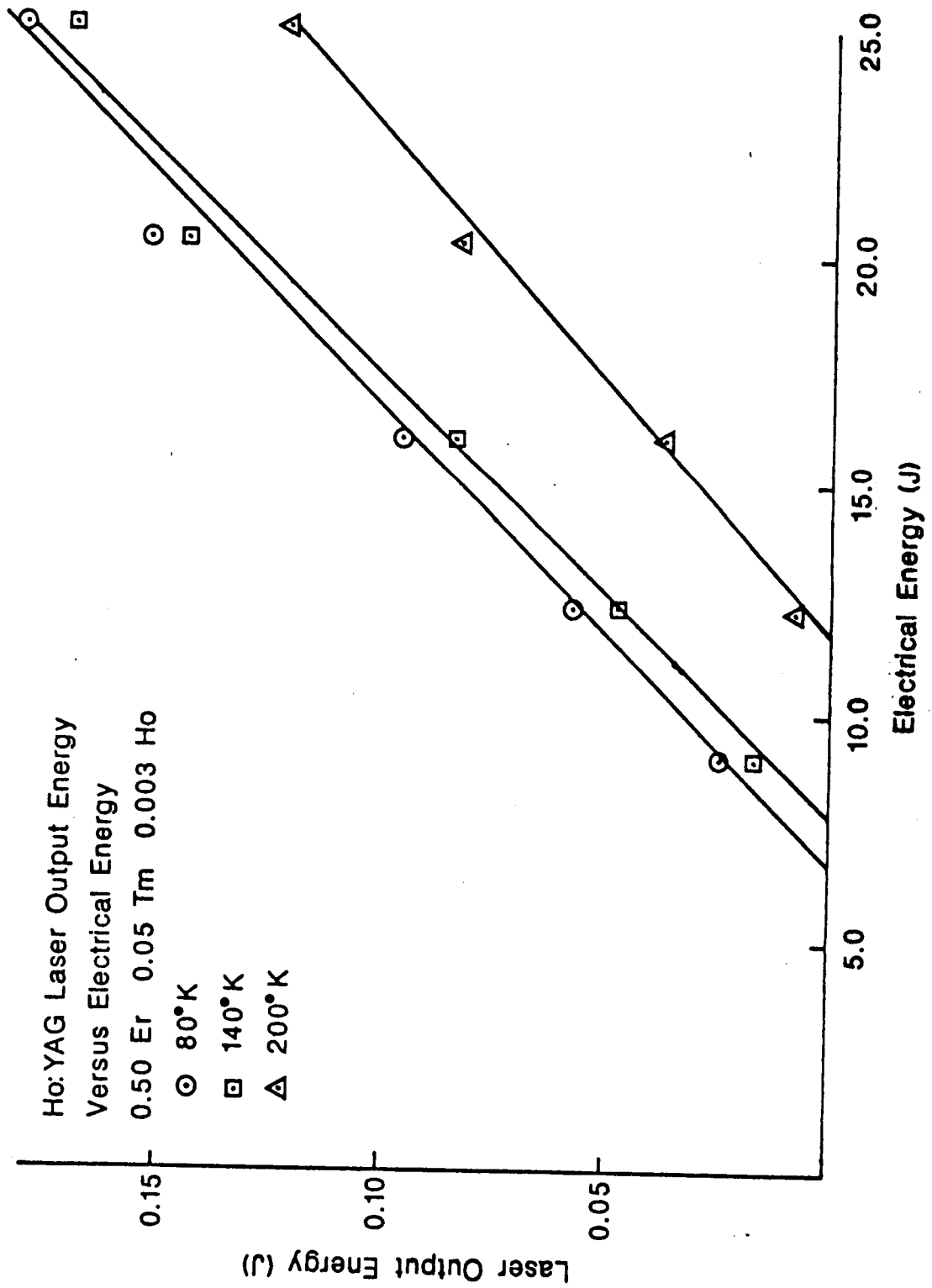
15000.00

18500.00

22000.00

Wavelength (nm)

in 10/16  
300K 1/15 nm excite



# HO:YAG EFFICIENCY

	PRESENT	PROJECTED
DIODE LASER	.50	.50
OPTICAL COUPLING	.80	.90
TRANSMISSION INTO CRYSTAL	.95	.95
ABSORPTION	.50	.60
ENERGY TRANSFER	.95	.95
OPTICAL EXTRACTION	.30	.60
Q-SWITCHING	.55*	.80
	<u>.03</u>	<u>.12</u>

\* WORST CASE ESTIMATE

## 2 MICRON STATUS

### ACHIEVEMENTS:

- CW LASERS HAVE DEMONSTRATED 30% POWER CONVERSION EFFICIENCY FROM 0.785 TO 2.1 MICRON AT ROOM TEMP.

### QUESTIONS:

- HOW WILL Q-SWITCHING IMPACT THE CW EFFICIENCIES?
- LINE NARROWING NOT DEMONSTRATED BUT EXPECTED

### FUTURE NASA PLANS:

- STUDY LASER CRYSTAL SPECTROSCOPY
- DIODE PUMP, INTRA-CAVITY Q-SWITCH
- PERFORM LINE NARROWING



## Report Documentation Page

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16. Abstract  The Second Combined Manufacturers' and Technologists' Conference hosted jointly by NASA Langley (LaRC) and the Federal Aviation Administration (FAA) in Williamsburg, Virginia, on October 18-20, 1988. The meeting was co-chaired by Dr. Roland Bowles of LaRC and Herbert Schlickennaier of the FAA. The purpose of the meeting was to transfer significant, ongoing results gained during the second year of the joint NASA/FAA Airborne Wind Shear Program to the technical industry and to pose problems of current concern to the combined group. It also provided a forum for manufacturers to review forward-look technology concepts and for technologists to gain an understanding of the problems encountered by the manufacturers during the development of airborne equipment and the FAA certification requirements. The present document has been compiled to record the essence of the technology updates and discussion which followed the session.			
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